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Make it with Micromite
Finishing the PicoMite smart light controller software

Audio Out
Designing a practical discrete audio op amp

GPS-Synchronised Analogue Clock

PicoMite smart light Controller

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 1 - Bookcase
 2 - Decking Flood Light
 3 - Dining Room Light
 4 - Dressing Table Striplight
 5 - Girls Room
 6 - Globe Light
 7 - Hall Light
 8 - Jenson's Light
 9 - Landing Light
10 - Lean-Too Lights
11 - Office Light
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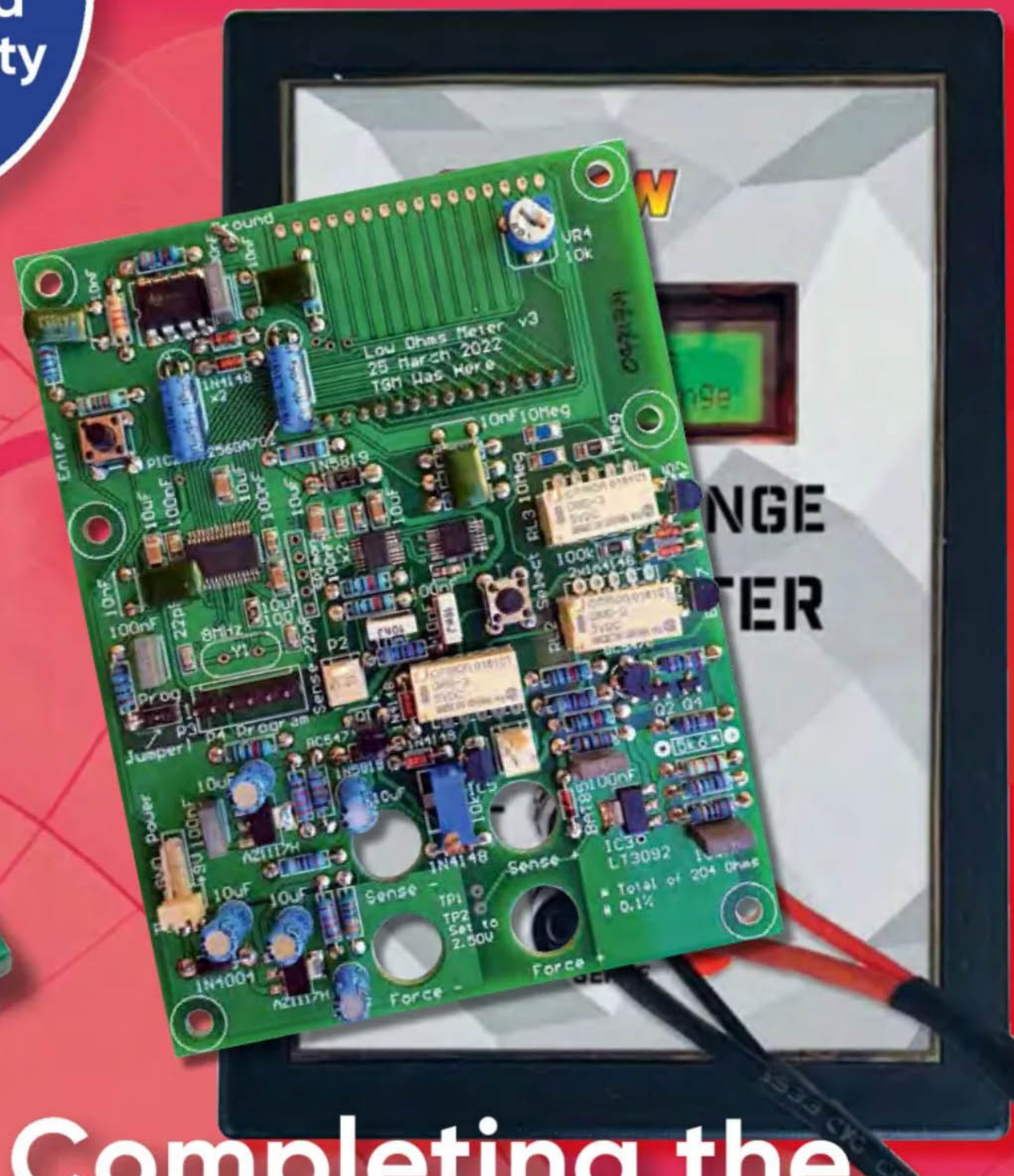
Mini LED Driver

Completing the Wide-range Ohmmeter



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Practical Electronics

Volume 52. No. 9
September 2023
ISSN 2632 573X

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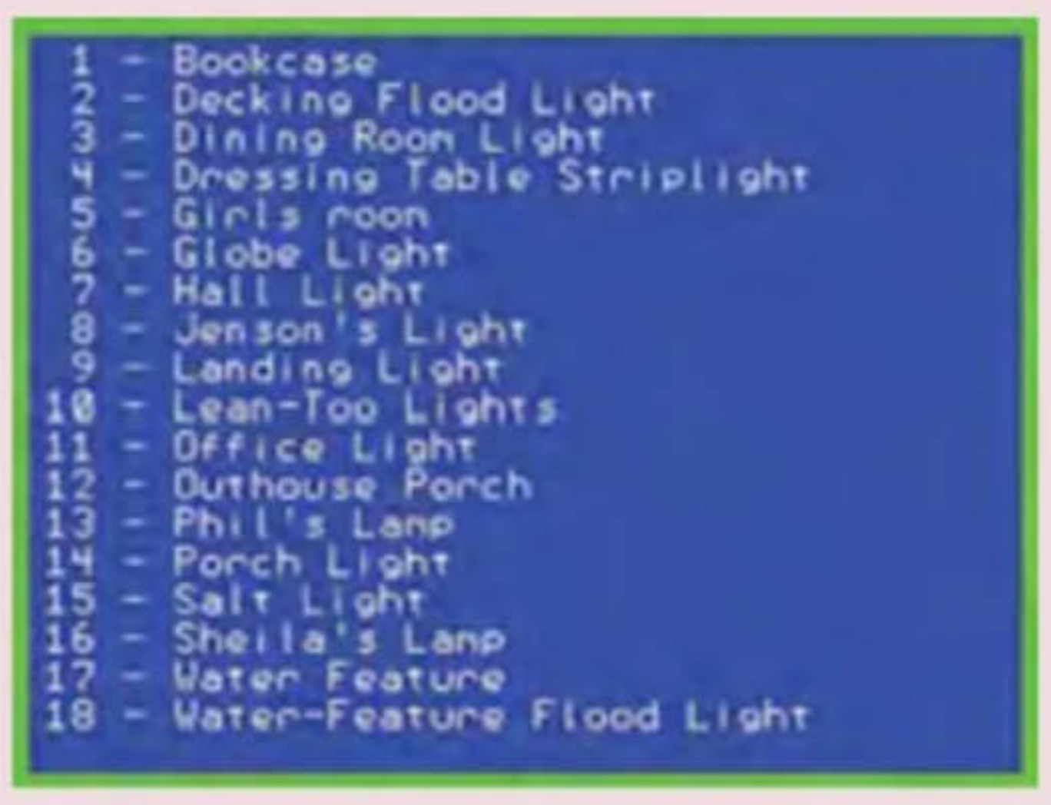

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The October 2023 issue of *Practical Electronics* will be published on Thursday, 7 September 2023 – see page 72.

WIRELESS FOR THE WARRIOR

by LOUIS MEULSTEE

THE DEFINITIVE TECHNICAL HISTORY OF RADIO COMMUNICATION EQUIPMENT IN THE BRITISH ARMY

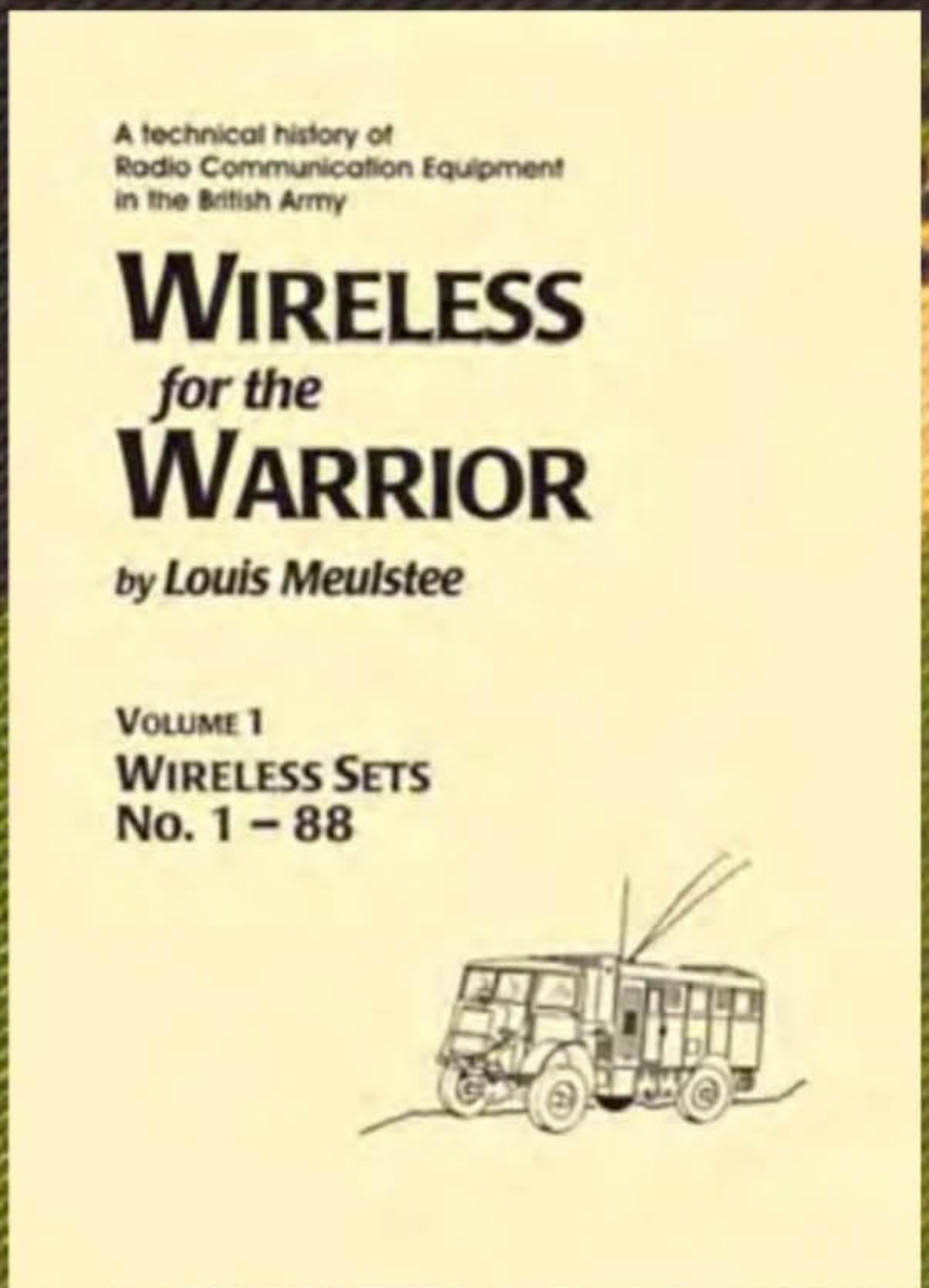
The *Wireless for the Warrior* books are a source of reference for the history and development of radio communication equipment used by the British Army from the very early days of wireless up to the 1960s.

The books are very detailed and include circuit diagrams, technical specifications and alignment data, technical development history, complete station lists and vehicle fitting instructions.

***Volume 1* and *Volume 2* cover transmitters and transceivers used between 1932-1948. An era that starts with positive steps taken to formulate and develop a new series of wireless sets that offered great improvements over obsolete World War I pattern equipment. The other end of this timeframe saw the introduction of VHF FM and hermetically sealed equipment.**

***Volume 3* covers army receivers from 1932 to the late 1960s. The book not only describes receivers specifically designed for the British Army, but also the Royal Navy and RAF. Also covered: special receivers, direction finding receivers, Canadian and Australian Army receivers, commercial receivers adopted by the Army, and Army Welfare broadcast receivers.**

***Volume 4* covers clandestine, agent or 'spy' radio equipment, sets which were used by special forces, partisans, resistance, 'stay behind' organisations, Australian Coast Watchers and the diplomatic service. Plus, selected associated power sources, RDF and intercept receivers, bugs and radar beacons.**



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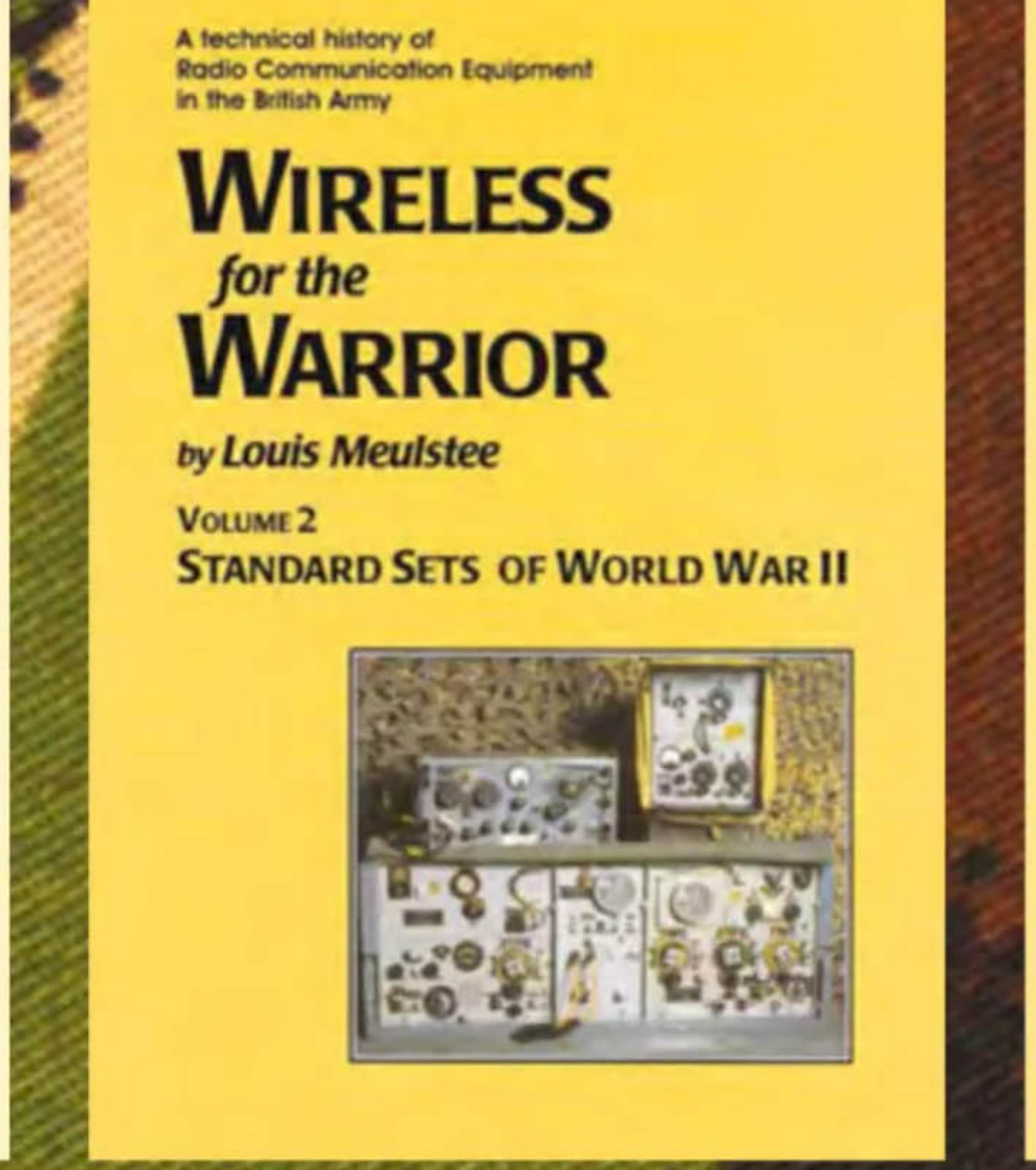

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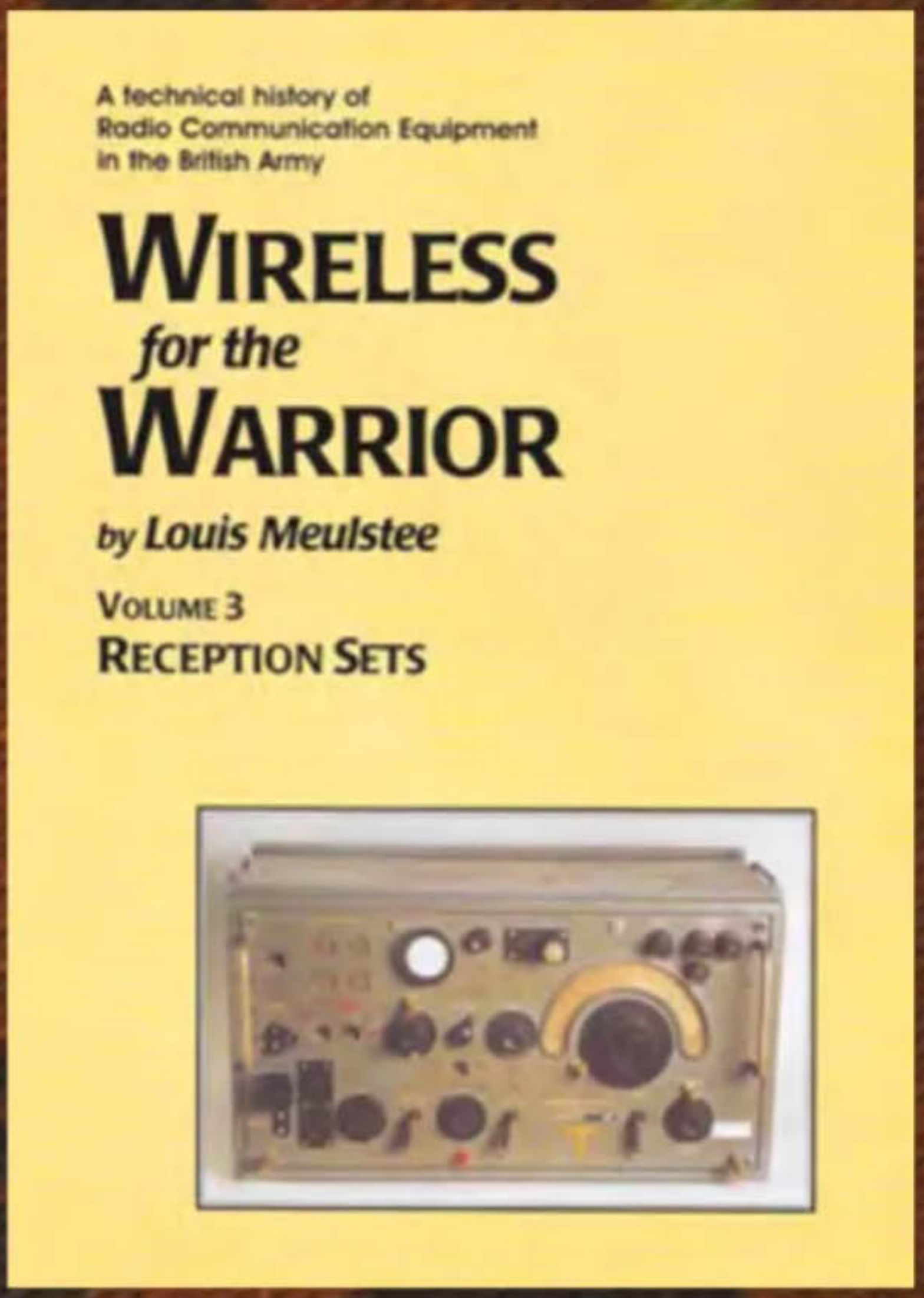

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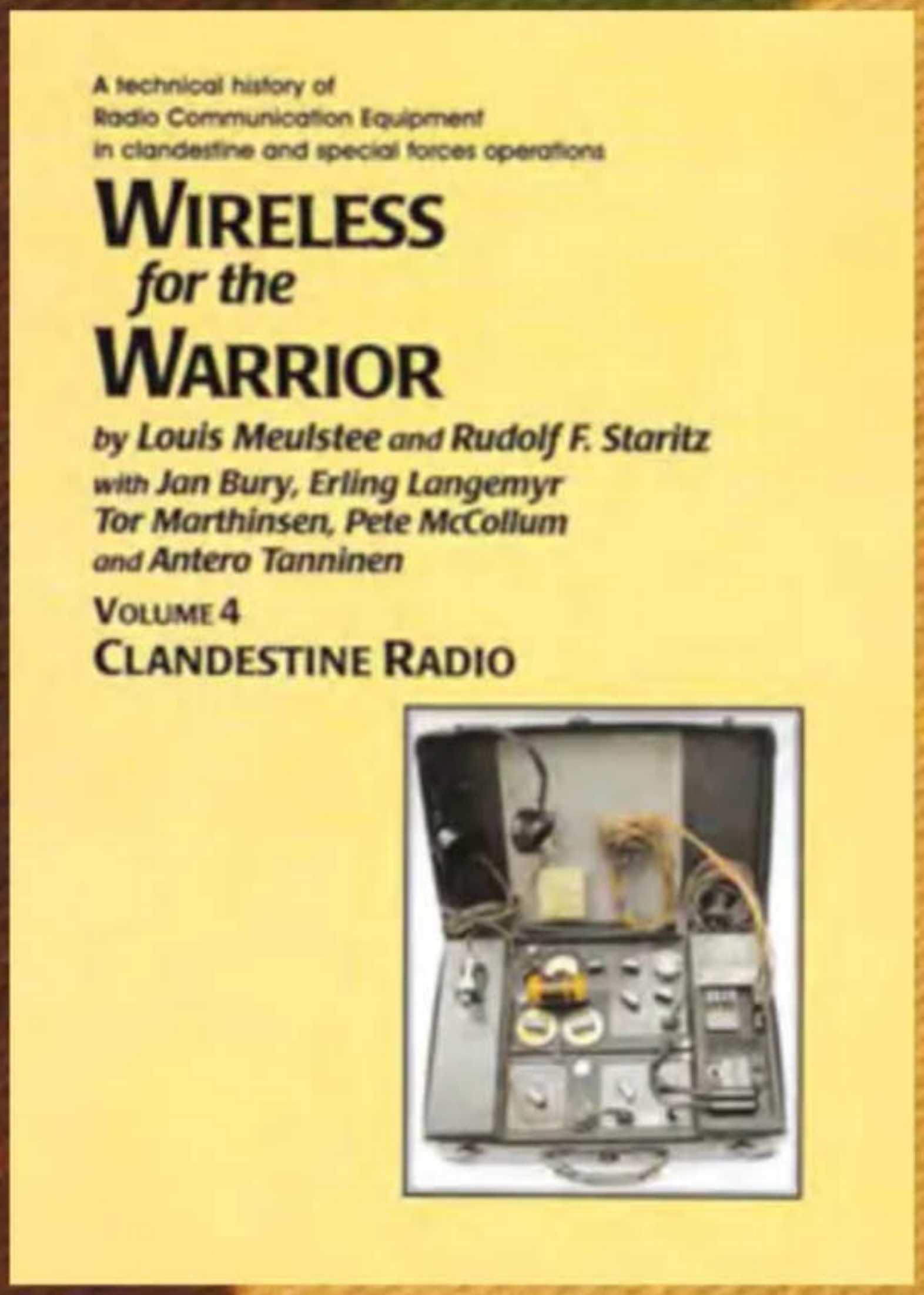

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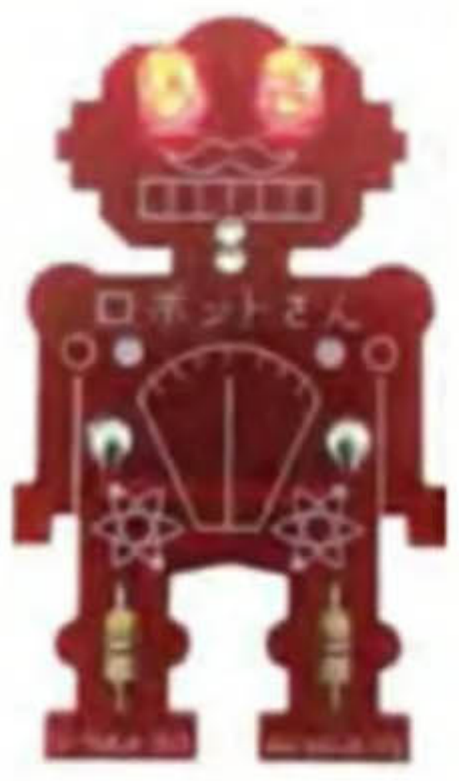

A fun, wearable electronic gadget that you can pin to your clothes. Easy to solder beginners kit. Two flashing bicolour LEDs resemble the eyes. 65 x 40 x 15 mm. CR2032 battery powered (not included).
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LED Electronic Dice Kit

Still popular! A must-build soldering kit for all beginners. Dice slowly rolls to stop on a random number when the push button is released. 9V battery (not included). Ideal for educational courses. Wide selection of component types.
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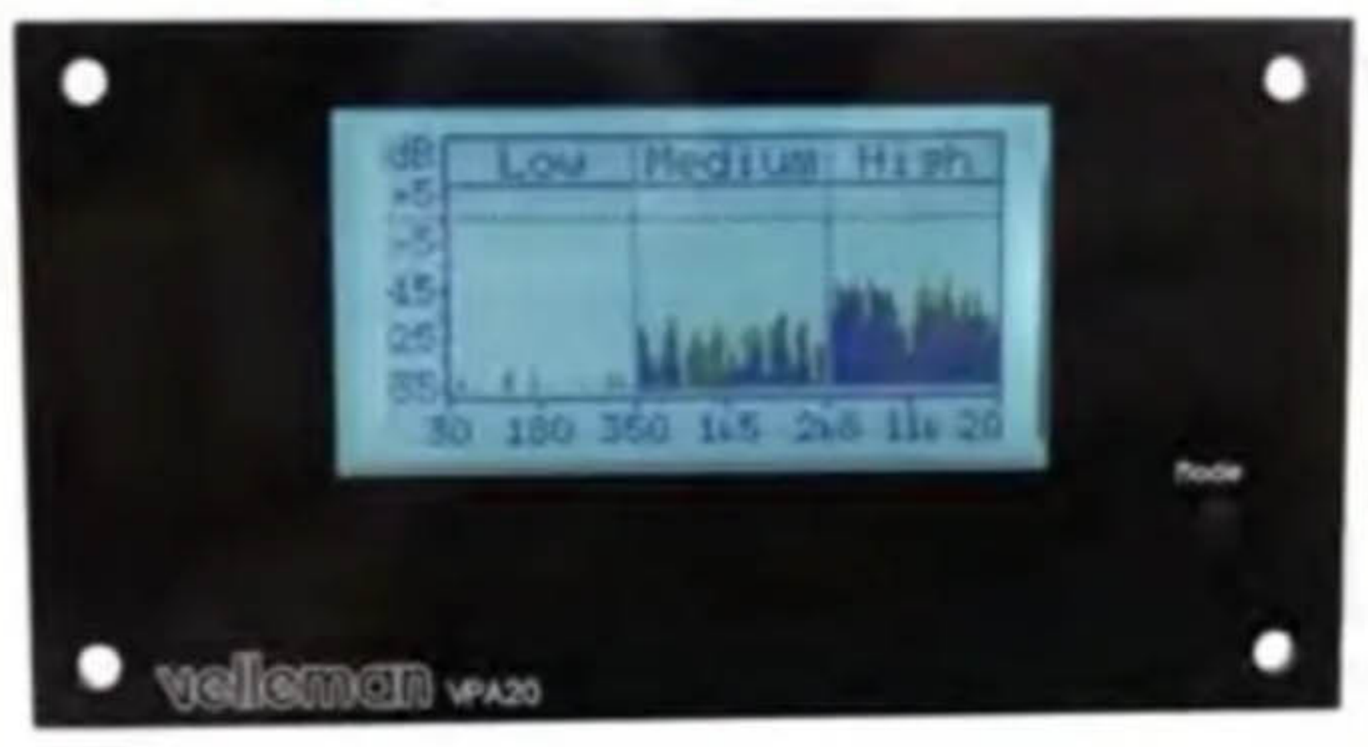

Small, compact LCD display, ideal for panel mounting. Give your homemade audio gear a high-tech look. Upgrade existing equipment. Provides Peak Power, RMS Power, Mean dB, Peak dB, Linear Audio Spectrum And 1/3 Octave Audio Spectrum. Auto / Manual range selection. Peak-hold function. Speaker impedance selection.
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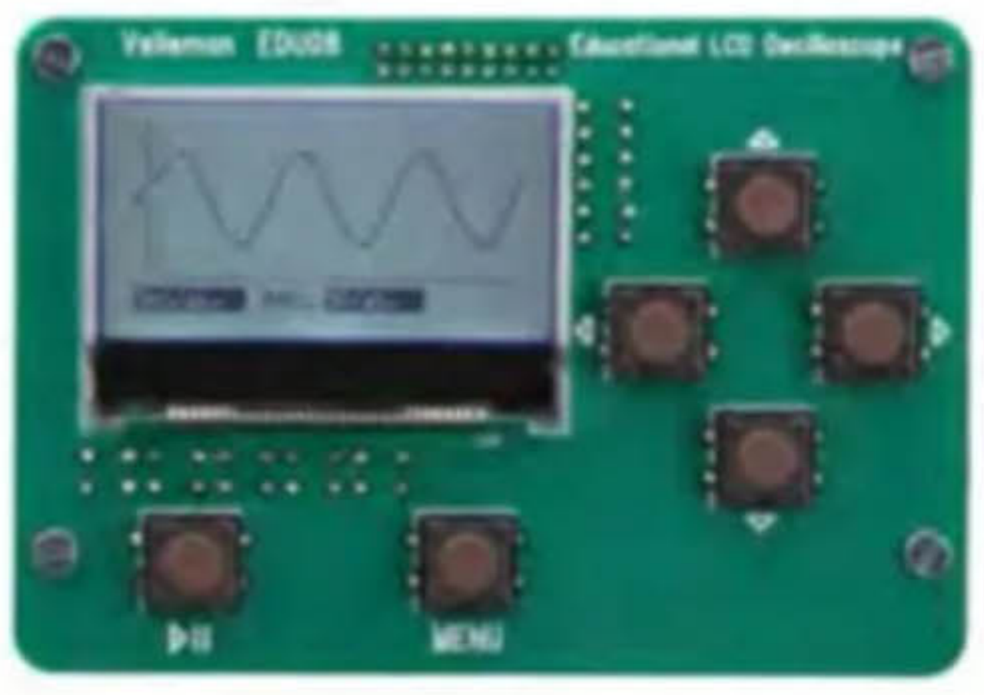

Build your own LCD oscilloscope with this exciting new kit. Learn how to read signals. See the electronic signals you learn about displayed on your own LCD oscilloscope. Despite the low cost, this oscilloscope kit has a lot of features found on expensive units like signal markers, frequency, dB, true RMS readouts and more. A powerful auto-setup function will get you going in a flash!
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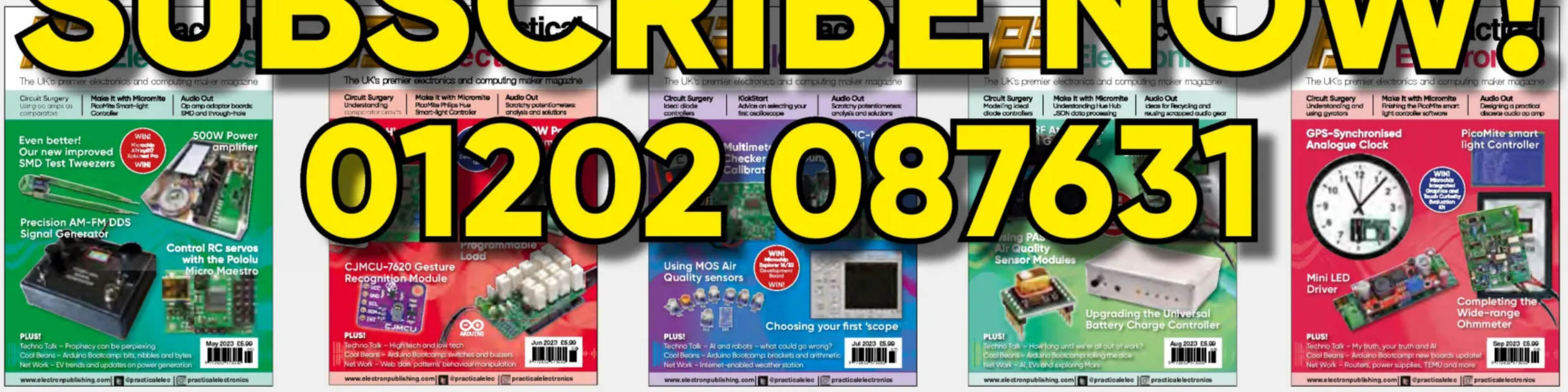

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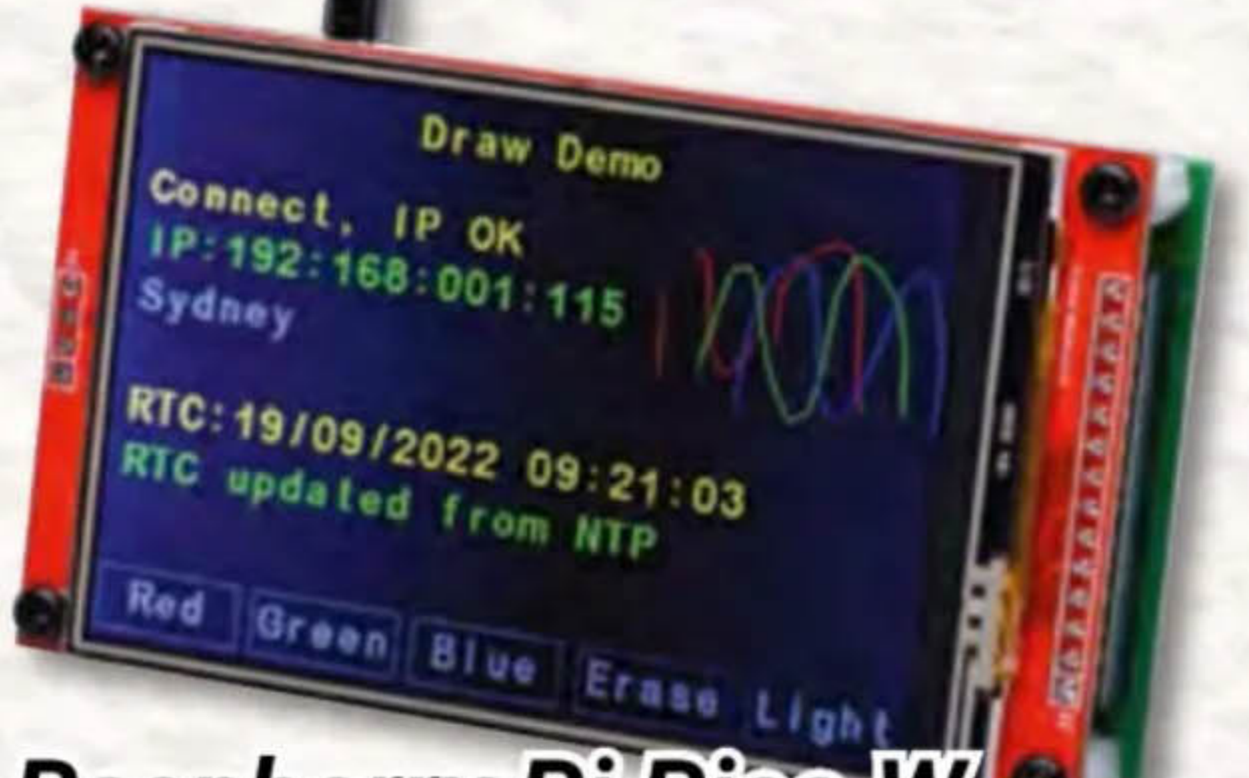

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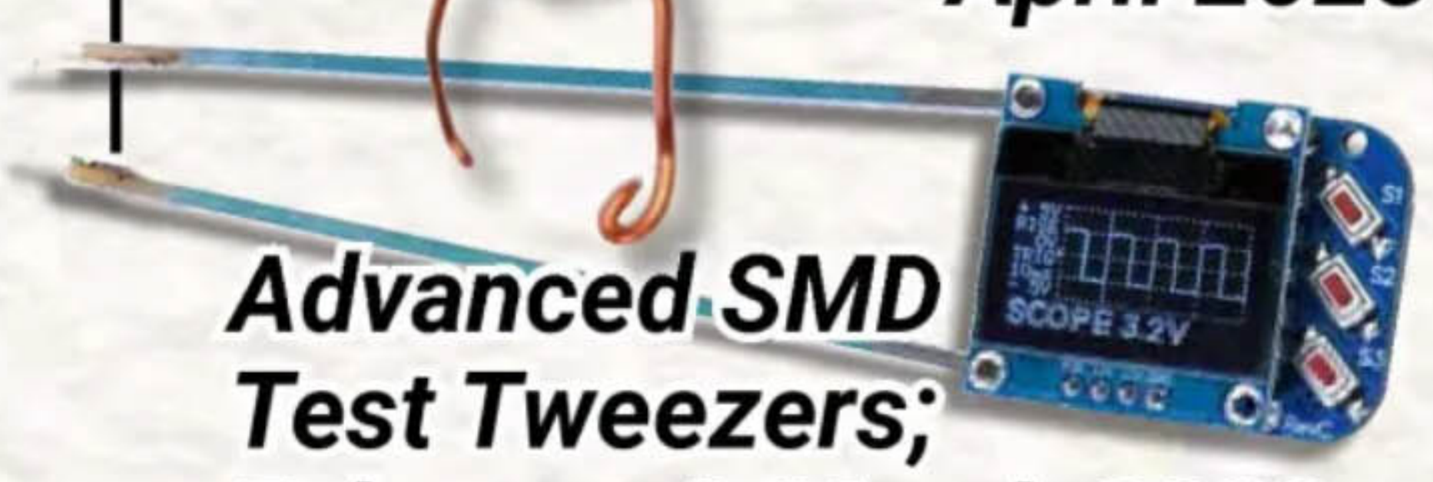

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Volume 52. No. 9
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Questions about articles or projects should be sent to the editor by email: pe@electronpublishing.com

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All reasonable precautions are taken to ensure that the advice and data given to readers is reliable. We cannot, however, guarantee it and we cannot accept legal responsibility for it.

A number of projects and circuits published in *Practical Electronics* employ voltages that can be lethal. You should not build, test, modify or renovate any item of mains-powered equipment unless you fully understand the safety aspects involved and you use an RCD (GFCI) adaptor.

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We do not supply electronic components or kits for building the projects featured, these can be supplied by advertisers. We advise readers to check that all parts are still available before commencing any project in a back-dated issue.

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I hope you are enjoying the summer, and whatever the weather is up to, you also enjoy the latest packed issue of *Practical Electronics*. We have some treats in store for you this month.

Super-accurate analogue clock

All the projects are good, but my favourite is definitively the *GPS-synchronised Analogue Clock*. It's the marriage of a classic dial-hands timepiece with the accuracy of digital technology. Geoff Graham – of Micromite fame – has designed an elegant combination of cheap electric clock technology, a PIC microcontroller and an inexpensive GPS module that offers fantastic accuracy. It even takes account of local daylight saving. You can fit his circuit to just about any electric clock and never have to worry about losing or gaining time. Geoff has even made it a low-power design, so it will run off a set of batteries for several years.

When it comes to telling the time I'm rather old fashioned – I do prefer to read time from a dial and so this is definitely a project I will build over the summer.

For those of you who like to build instrumentation, this month we finish the *Wide-range Ohmmeter*. It really is a must-build for all you analogue fans, especially if you regularly need to measure very small resistances.

Plus, we have a nice compact *Mini LED Driver* project that will find uses in dozens of application… basically wherever you want to drive large 12V white LEDs!

Gyr… what?

Ever heard of 'gyrators'? They are an interesting concept – related to transformers, inductor and capacitors – but different! One of the nice things abut them is you can use them to mimic inductors without having to use a wound component. In certain circuit scenarios this offers real advantages. I thank you'll enjoy Ian Bell's thorough *Circuit Surgery* explanation.

Need a book? – Part 2

Finally, I mentioned last month that if you hunt hard enough on Amazon (and other online retailers) then there are some real bargains to be had with second-hand electronics books. I stand by this, but Julian Edgar – our *Electronics Building Blocks* scribe, and also a published book author – wrote to me to point out that hardworking writers don't get paid from second-hand book sales! He's right of course, so if you want to support writers, who rarely get well paid, then do buy new if you can afford it!

Matt Pulzer
Publisher

Techno Talk

We both have truths, are mine the same as yours?

Max the Magnificent

We live in interesting times. Not so long ago, everyone living somewhere like the UK was exposed to the same sources of news, and those sources did their best to maintain the integrity of their content. If only we could say the same today.

There's an old expression that 'History is written by the victors.' This means that, although certain things may or may not have happened, the eventual record of what occurred is documented by people with power and influence who at best were there and saw it (if we're lucky) or who just heard or read about it (if we're not). Either way, they cast their own interpretation of what happened under the influence of social, political and personal considerations.

There's also the fact that most of us don't have great memories to begin with. Actually, that's not strictly true because my dear old mother's mind is so sharp that she sometimes remembers things that haven't even happened yet. Be that as it may, in many respects the way our biological memory systems work is awesome overall, it's just that most of us aren't tremendously talented with respect to remembering specific happenings. Things are further complicated by the fact that our memories are coloured by our emotional state at the time an event takes place. And none of this is aided by the fact that the way our minds work means that every time we recall something, we inadvertently tweak that memory and end up storing a slightly revised version.

As a result, since the dawn of time, people who experience the same event may recall it in very different ways. I offer myself as living proof. Whenever I do anything with my wife (Gina the Gorgeous), sometime later, when she tells the tale of our adventure to a third party – like her mother, for example – it's as though I attended a completely different event (usually one for which my presence was surplus to requirements).

That may be one of the reasons people were so excited by the advent of photography, as epitomised by the oldest surviving photograph of an image formed in a camera, which was created by the French inventor Joseph Nicéphore Niépce circa 1827. By the 1850s, printed photographs were starting to become available to the general public. At that time, most people assumed that a photograph offered a faithful depiction of a scene, which led to sayings like, 'The camera never lies'.

As we now know, of course, the camera rarely tells the truth. Some people lay the blame on the creators of digital image editing applications like PhotoShop. In response, I would suggest that these simple souls search for 'Cottingley Fairies' on Google.

Dire doings being done

Most of the time, photos are altered for artistic or commercial effect. It's unfortunate that some nefarious scoundrels modify media with maleficent motives. All of which leads us inexorably to the topic of deepfakes (a portmanteau of 'deep learning' and 'fake'). This involves using artificial intelligence (AI) and machine learning (ML) to manipulate or generate synthetic media in the form of audio and visual content. For example, take a tool like Lyrebird – **https://bit.ly/3NGDpYr** – which can listen to someone talking, or a recording of someone talking for a couple of minutes and extract a 'digital signature' of that voice. Later, using a text-to-speech mode, it's possible to create a recording of that person apparently saying whatever you want them to say. I'm sure this capability will come in handy for all sorts of legitimate purposes. What could possibly go wrong?

Where things start to get really scary is when an AI is used to analyse videos of someone talking. Using natural language processing (NLP) to understand what's being said (one part of understanding the emotional content of the message), the AI can analyse the video frame by frame and associate phonemes (units of sound that distinguish one word from another) with lip movements and other facial phenomena (blinking, squinting, grinning, grimacing…).

Later, if presented with an audio recording (a recording that could be generated by a tool like Lyrebird), the AI can generate a frame-by-frame photorealistic video of that person saying whatever you want them to (appear to) be saying.

Fake news!

One of the things I didn't fully appreciate when I lived in England was the quality of the news. After spending the past 33 years of my life listening to the drivel they call news here in the US, hearing the dulcet tones of a BBC news announcer explaining what's actually happening without offering their personal interpretation brings a little tear to my eye. The news channels over here are so far apart, and some are so divorced from reality, that reports of the same happening suggest the events they describe occurred on different planets.

The same thing happens with newspapers. I know that the tabloids in the UK tend to lean one way or the other politically speaking. As I recall, however, at least you used to get the impression they were reporting the same thing, albeit from their own perspective (I hope this is still the case). Once again, things are more dire here in the US.

And then there's the fact that many people now obtain their news from social media channels whose algorithms are tuned to keep on feeding each viewer more of what they like, which boils down to them only seeing things that reinforce what they already believe to be true.

Things are further confused by the advent of generative AIs like ChatGPT, whose models are trained on open-source material that may have inbuilt biases and inaccuracies. As Pontius Pilate says (well, warbles) to Jesus in Andrew Lloyd Webber's *Jesus Christ Superstar*, 'And what is 'truth'? Is truth unchanging law? We both have truths. Are mine the same as yours?'

Is there an answer to all this? Personally, I'm longing for the day when my AI-powered augmented reality (AR) glasses highlight misinformation in text (with associated links to validated sources), they add pop-up information bubbles to correct misrepresentations on television, and they pre-emptively whisper 'they're lying' in my ear whenever a politician opens his or her mouth. (What? Cynical? Moi?)

Exclusive offer

Win a Microchip Integrated Graphics and Touch (IGaT) Curiosity Evaluation Kit

Practical Electronics is offering its readers the chance to win a Microchip Integrated Graphics and Touch (IGaT) Curiosity Evaluation Kit (EV14C17A) – and even if you don't win, receive a 15%-off voucher, plus free shipping for one of these products.

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The Integrated Graphics and Touch (IGaT) Curiosity Evaluation Kit uses the SAME51J20A 32-bit microcontroller from Microchip Technology to implement a minimised chip-count graphics and 2D touch screen solution for cost-sensitive applications without performance compromises.

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This design is ahead of all other Arm Cortex-M4 touch and graphics solutions on the market because it eliminates the need for a dedicated touch controller and the need for tuning the controller, reducing cost and complexity. All firmware, including the graphics and touch library and demo applications, is publicly available through the integrated MPLAB Harmony v3 Framework.

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Microchip Integrated Graphics and Touch (IGaT) Curiosity Evaluation Kit

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Closing date

The closing date for this offer is 31 August 2023

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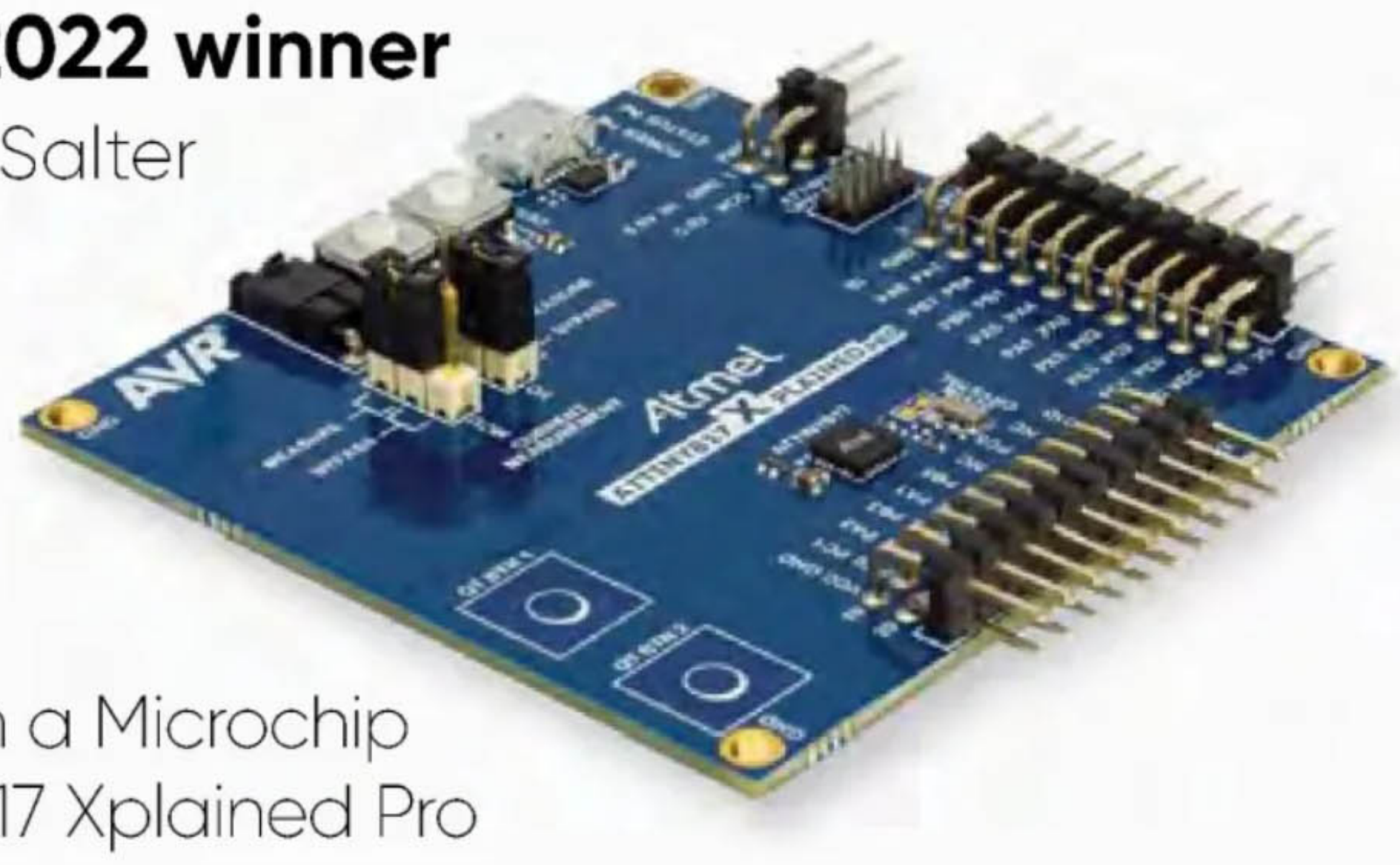
Shaun Salter



He won a Microchip ATtiny817 Xplained Pro

Cures for online pain and frustration

Online purchasing can be a painful experience. If something goes wrong, raising a query all too often drops you into unresponsive, unhelpful and obstructive bot-based 'Help and response' systems. Last month, I gave an example. This month, I bring some hopeful news of a simple way to bypass or over-fly obstructions.

Pass the parcel from eBay

As a brief reminder, I bought a £50 bit of electronic kit from an eBay seller (flat price, no auction bidding) which was (allegedly) sent to me by Royal Mail Tracked Delivery. It never arrived. The seller claimed 'proof of delivery' in the form of Tracking Data from Royal Mail. But the Data was clearly phoney. There was no address for actual delivery, no photo evidence of delivery and the package had been 'signed for' with two different names and scribbles – both fictional.

For reasons I have never understood (perhaps due to over-dependence on a bot) eBay accepted the demonstrably fraudulent tracking data as solid proof of delivery, rejected my claim, closed the case and – when I complained – told me (several times) to contact Royal Mail and get Royal Mail to admit failure to deliver.

'Royal' Mail

As a reminder, Royal Mail has since 2015 been a private company owned by shareholders. Quite how it retains the Royal seal is a mystery. Ofcom recently opened an investigation into Royal Mail's compliance with its quality-of-service statement.

Royal Mail flatly refused to help investigate the phoney 'proof of delivery', saying it would not 'further investigate.... due to the time that's passed'. In fact, only one week had passed between notifying eBay of goods missing and eBay rejecting my claim and telling me that I 'must contact Royal Mail'; and only one day had passed between eBay rejecting my claim and my contacting Royal Mail. A full week later Royal Mail was still writing 'if your item still hasn't been received', thereby suggesting that the package might just have been delayed by Royal Mail's rotten service.

Royal Mail showed no interest in the signature fraud and said eBay had 'misadvised' in telling me to contact Royal Mail because any queries on tracking data must be made by eBay and the seller. As eBay had already closed the case, and the seller already had my money, there was fat chance of that.

Escalation

But after (and only after) I filed an Escalated Customer Resolution complaint about Royal Mail's customer service, a Royal Mail employee grudgingly confirmed – after just short of a month of my nagging – that 'the GPS attached to the scanning equipment… does indicate that the item has been misdelivered to an incorrect address.'

'Due to Data Protection Regulations, (Royal Mail is) unable to disclose the address in question,' wrote Royal Mail, blaming the now universal legal scapegoat.

In the meantime, I used the surprisingly easy-to-use online process for filing a Police Crime Report. To cut a longish story short, police officers visited, spoke to me by phone, emailed for further information, issued a crime reference number and confirmed in writing that the phoney Royal Mail Tracking Data relied on by eBay 'should be considered a fraud by false representation as someone has represented they are you to obtain these goods'.

So far so good. But when the police tackled Royal Mail, using a dedicated direct crime-stopping contact number (which incidentally Royal Mail only answers on weekdays) the police faced the same roadblock that I as a member of the public had run up against.

Still no help from Royal Mail

Royal Mail flatly refused to give the police the address of actual delivery unless the police filed a formal 'RIPA' (Regulation of Investigatory Powers Act 2000) request. RIPA governs the use of covert surveillance by public bodies and in practice the police only

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invoke the time-consuming process for serious crimes or thefts. The police could not understand why Royal Mail was insisting on a RIPA and a fifty-quid bit of kit could not justify the time and cost involved.

A helpful, and obviously frustrated, police sergeant, explained: 'If we can move fast and knock on a door, missing parcels have a way of suddenly appearing. But Royal Mail have insisted that there is no way other than RIPA for the police to get the address and investigate the fraud. And it's now taken so long that the evidence will have gone so the power of arrest will have also gone.'

So, thanks a million Royal Mail for your part in the fight against postal fraud by taking nearly a month to check your GPS proof of fraud and then refusing to share it with the police. Maybe, purely as a probably pointless personal experiment, I will try pursuing Royal Mail through to the Ombusdman. Maybe not. I'll see how I feel.

eBay's NoReply approach to communication

If communicating with Royal Mail over self-evident fraud is frustrating, it can't hold a candle to communicating with eBay. Even the police found it frustrating. Once the standard 'where are my goods' customer procedure has been completed and shut down, eBay sends emails from a NoReply address. The only way (that I could find) then to challenge an eBay email is to wade through an ocean of automated FAQ treacle and use a web form to initiate a completely new enquiry. This is then dealt with by someone fresh to the case. There is no provision (that I could find) to attach photographs or documentary evidence.

It would be good if there were a way to complain to the Ombudsman about eBay. And according to eBay there is. The company directs disgruntled customers to the Financial Services Ombudsman – see: **https://bit.ly/pe-sep23-ebay**

Not so, says the FOS, 'We are a free service set up to resolve disputes with financial businesses, like banks or insurance companies… and it doesn't appear your complaint is one we can help with.'

Chargeback

Fortunately, there is still one near-magic way to bypass eBay's obstructions. It's called Chargeback and it's a service offered by the credit card companies.

Essentially, if you have paid for goods or services with your credit card and something has gone wrong, you can use the credit card company's online system to claim back the payment made from the card. If the credit card company agrees that you have been done down, it will claw back the cash.

Chargeback will usually, initially, be only temporary, though. If the other side contests the claim, the credit card company will ask for more evidence and evaluate it. But this evidence can be sent by email, with evidence attached.

The big glory of the Chargeback process is that there is no longer any need for the customer to try and deal directly with eBay and its deliberately evasive NoReply mail system.

In my case, my card company temporarily clawed back my money from eBay. The eBay seller then responded by simply parroting his original reliance on the Royal Mail Tracking Data that I had repeatedly shown to be phoney.

Because I had filed a crime report I was able to show evidence quoting the police crime reference number and police letter deeming the signatures to be fraudulent. Moral: if you have been burned online, file a crime report, if only for the Crime Reference number.

Since I had escalated my complaint to Royal Mail and finally squeezed out written admission of delivery to a wrong address, I was able to file that also as evidence. Moral #2: if Royal Mail Customer Help is unhelpful, use the escalation option.

So far, the money remains in my account and like a plaintiff in court I can now only wait to see whether and how eBay and the phoney-proof-parroting seller respond to the shed load of evidence I sent the card company, and what the credit card 'jury' decide on where my £50 should finally come to rest.

Regardless of the outcome, I already know one thing for sure. I shall think very carefully indeed before I ever again buy anything costing more than a few quid through eBay, or buy anything from anyone who wants to send it by Royal Mail Tracked Delivery.

…and finally

Last, here's one other practical tip. All today's complaints and claim services will usually have a tight limit on the number of text characters that can be submitted as a description of the complaint. If they allow photo or documentary evidence to be filed there will usually be restrictions on the file format and size accepted. This may well not be clearly stated in advance. So ahead of starting on the claim or complaint trail, draft a tight statement of fact with all the most relevant dates and events clearly set out. Also, collect and collate all the evidence, ideally as widely accepted jpeg and pdf files. It will then be (relatively) easy to trim the word length and re-size files to comply with whatever online strictures pop up. As any writer knows, editing down facts is always easier than adding and expanding them.

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Net Work

Alan Winstanley

This month's column has a practical angle, looking at broadband router choices and advice about choosing quality mains adaptors. Aspects of DC connectors and USB charging are discussed, and there's a new online shopping mall to try.

A few weeks ago, my home network went down late one night without warning. The outage brought my workflow grinding to a halt, but it also reminded me how Internet and network access had become an essential utility in many households. I delved under the desk to check the simple things first: swapping Ethernet cables around and jiggling them in their Ethernet ports just to make sure everything was secure, but to no avail.

The weakest link

I then found that my multitude of smart lights and sockets, streaming TV sets and smart displays, speakers, Internet radios and security cameras had packed in as well, along with Wi-Fi, the home area network, and network storage and shared drives. In total, more than two dozen devices and gadgets that needed network access had all stopped working.

My ISP confirmed my broadband supply to be in order, so everything pointed to a problem with my router. My trusty Billion 7800N dual WAN router is over a dozen years old and was designed for heavy SOHO use; it's powered up 24x7 and had never missed a beat, thanks partly to its roomy, well-ventilated plastic housing which helps with cooling. However, this model uses a separate BT Openreach modem which is hooked to the telephone socket. Both the modem's power and 'DSL' LEDs were glowing, proof positive that the broadband was up and running (like my ISP said), but the modem's 'WAN' LED was off, a sign that the router itself wasn't working for some reason.

I found that none of the router's port status LEDs were illuminated either but, strangely, the router's power LED was flashing very faintly. Checking the mains adaptor with a multimeter, the DC output measured 12V as expected, so I guessed there must be an internal router fault. I dreaded the thought of having to source a new one with all the set-up, disruption and configuration hassles that would go with it.

That flickering power LED had raised my suspicions though, so I fetched a laptop-style variable voltage PSU set to +12V, and I jury-rigged a DC connection to the router. I switched on to see what would happen – and it worked! The network burst into life again. The router's switched-mode mains adaptor was obviously the culprit – measuring 12V no load, I found it had some sort of internal fault that shunted the output when under load, which would keep power-cycling the router – hence the flickering power LED. For a few days my entire network limped along like this until I could source a quality mains adaptor, a topic that I cover shortly.

The TP-Link TL-MR6400 is typical of the latest Wi-Fi routers, and it has a SIM fail-over slot to carry a SIM card backup. It needs a separate modem.

The route ahead

If a router replacement is on the cards, then it's worth trying to buy one that's as futureproof as possible. I was surprised by the limited choice of routers now available online – I guess most customers use the hubs provided by their ISP, though working-from-home and the semiconductor shortage had possibly affected supplies too. There were a few menacing-looking routers made by Netgear, D-Link and TP-Link, some very expensive models from Draytek and a handful of low-cost ones from the Chinese Tenda brand. Some Wi-Fi routers only offered 2.4GHz, not 5GHz, which is an essential choice for the future, so check those specs closely.

The latest routers offer Wi-Fi 6 and dual or triple bands and many now have built-in modems. A few have a SIM-card 'fail-over' slot for a SIM

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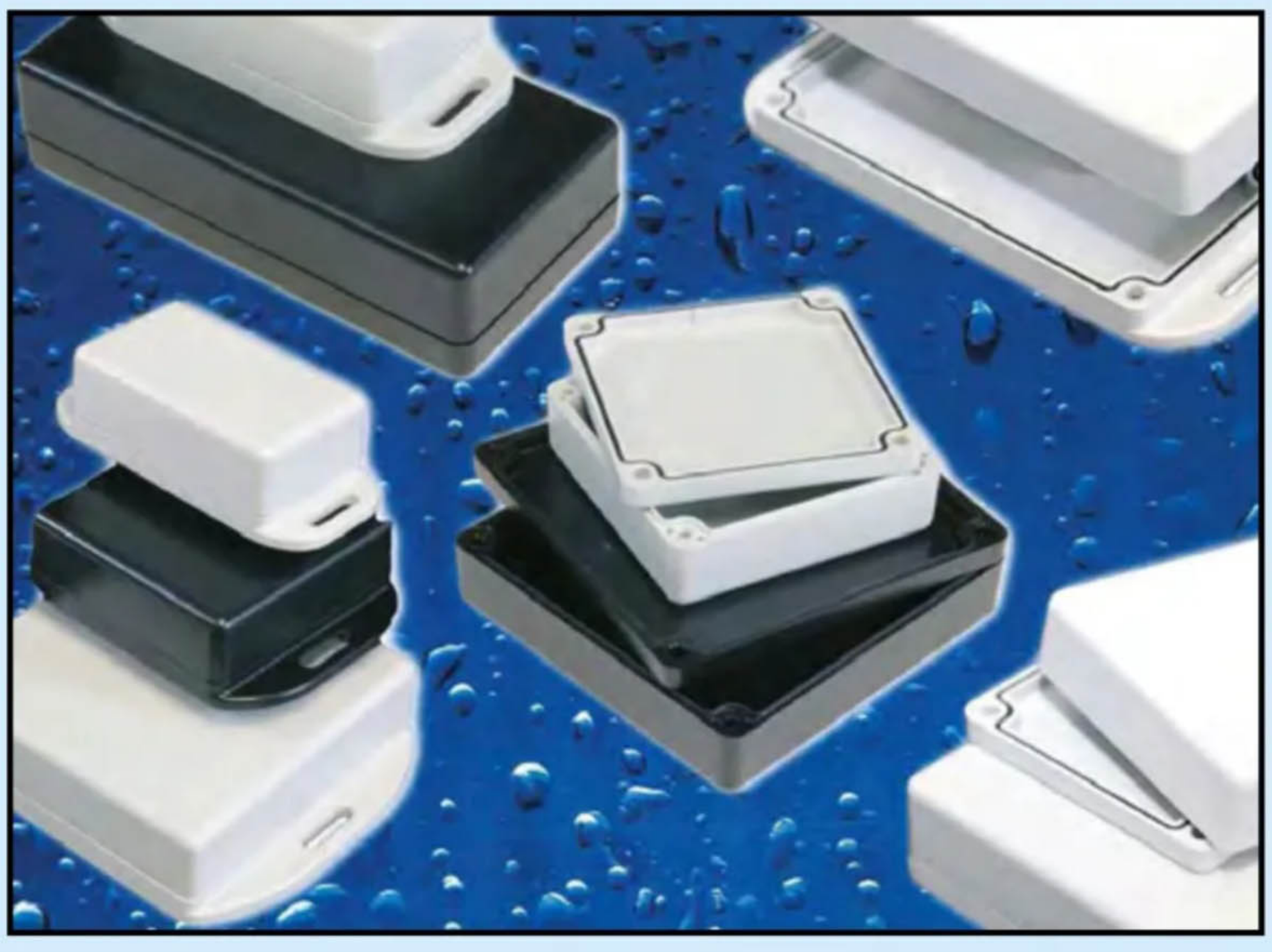
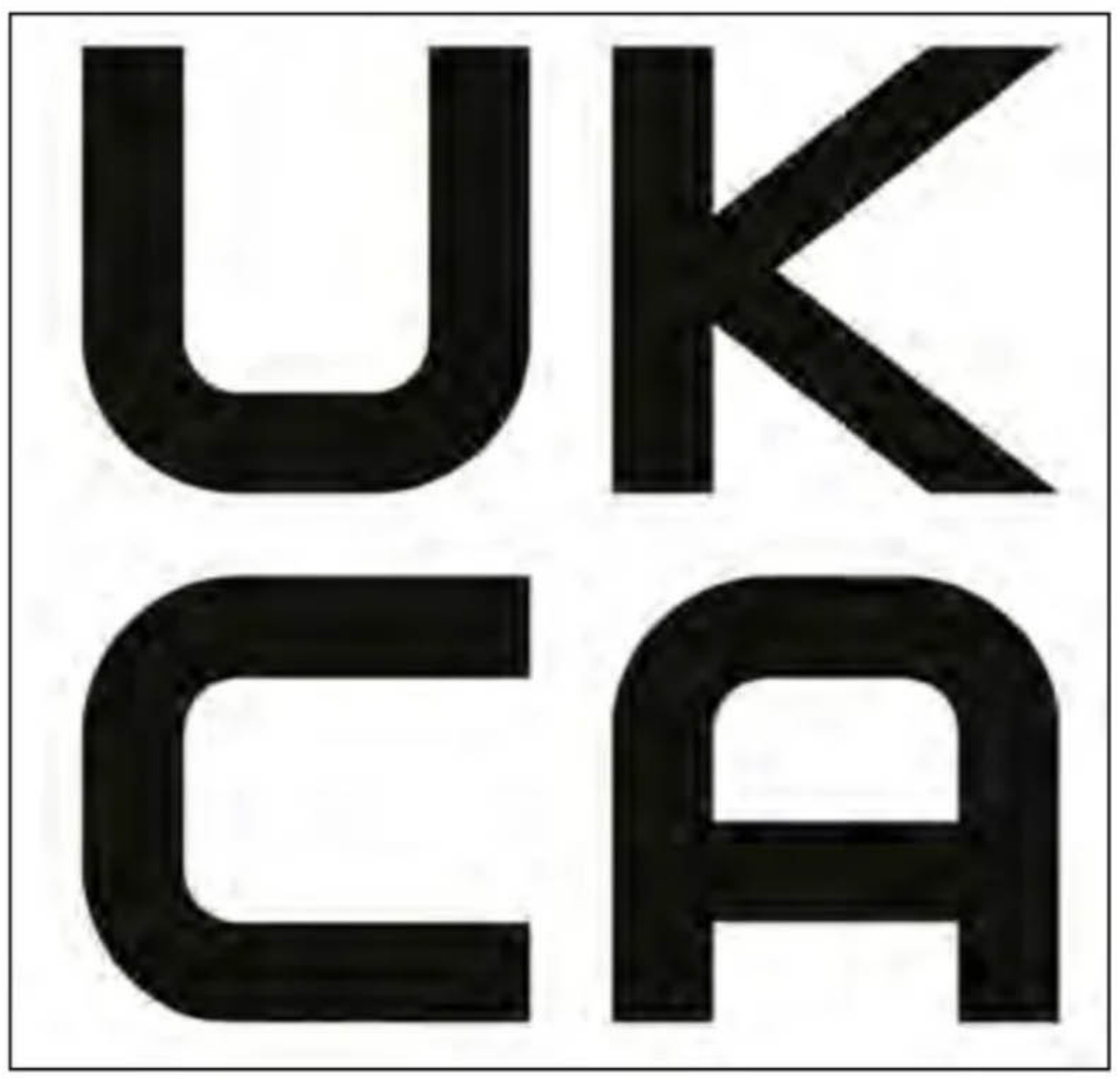




The UKCA conformance mark is starting to appear on electronics sold in Great Britain. The EU's CE mark will be superseded in Britain from 2025.

card data plan, a backup in case the main broadband goes down: the spec sheet will mention '4G/ LTE' somewhere. One example is the TP-Link TL-MR6400, which costs about £75, though higher-spec models cater for more demanding users. These routers need a separate modem, but for some reason stand-alone modems seem to be thin on the ground. One of the very few contenders is the Draytek Vigor 166, which costs £125 from the BT Shop. It turns out that many legacy BT Openreach VDSL modems (like the one screwed underneath my desk) were originally made by Huawei, and the Huawei Echolife HG612 ('3B' version) is the most desirable one. I found several used ones on eBay costing just a few pounds – I've bid on one which I'll keep as a spare!

A whole-home mesh router is another option for upgraders, and major brands each have their own mesh product ranges. Amazon now owns Eero, the pioneer of whole-home mesh; TP-Link sells Deco Wi-Fi mesh; Netgear offers Orbi; D-Link's mesh system is called 'Covr'; and Tenda sells Nova. D-Link also offers Wi-Fi 6 routers that are mesh-ready. My Mercusys (by TP-Link) mesh system is adequate for now though, and I was relieved to patch up my network for the price of a £12 mains adaptor – a bargain!

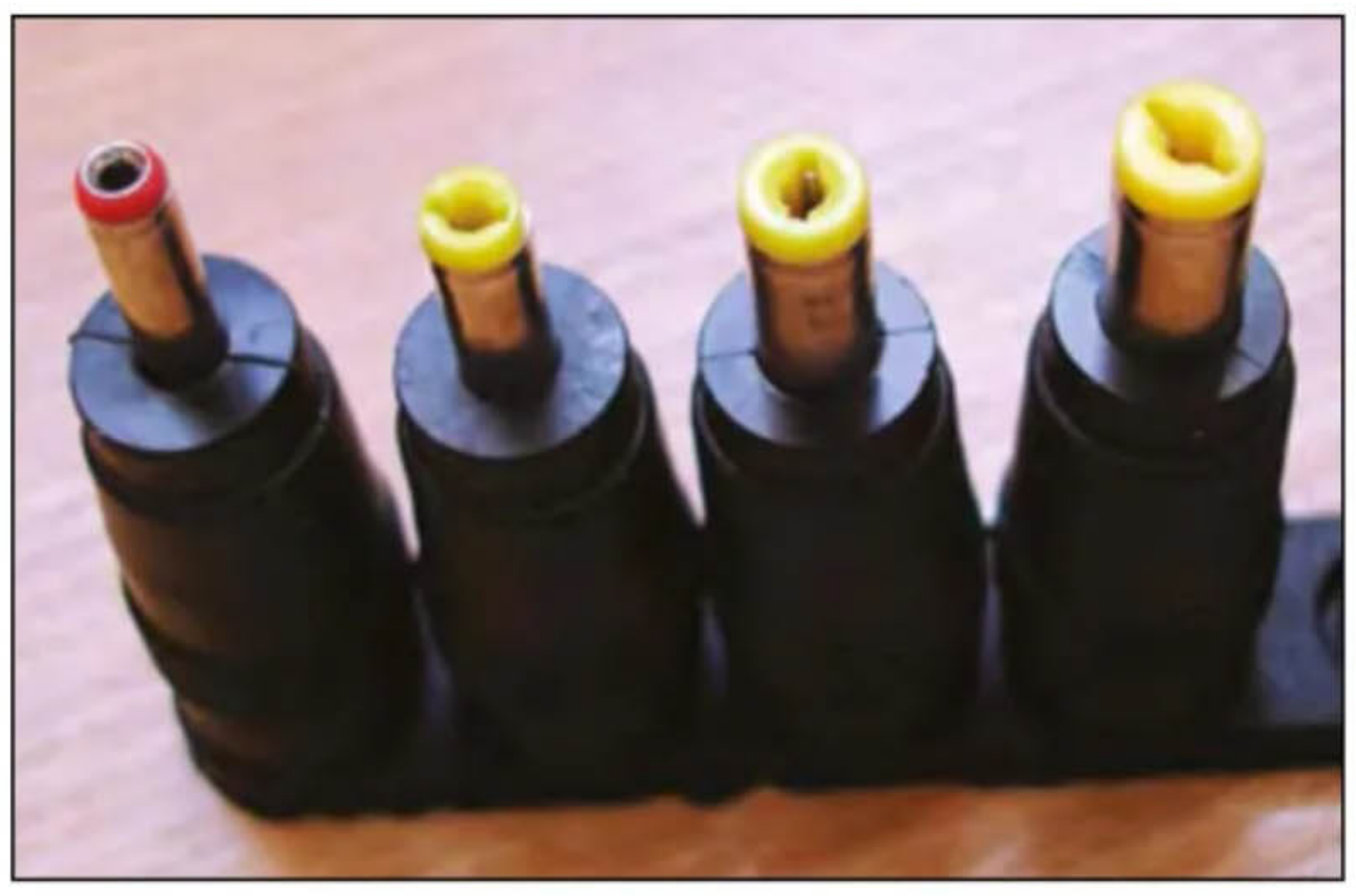
Power mad

As every *PE* reader knows, mains adaptors, wall warts, power bricks, whatever you call them, are used by most mains-powered low-voltage devices: there are nearly 20 adaptors near my desk alone. Hot and heavy transformer-based PSUs have been replaced by compact, lightweight switched-mode types, and consumer products increasingly use a 5V USB-type mains adaptor. So many USB chargers now litter the planet that some makers now omit mains adaptors from their products altogether and consumers have to provide their own.

While sourcing a new mains adaptor for my router, I found a huge variety of unlabelled types on all the usual websites. I avoid cheap unbranded ones that have no manufacturer's details, as these are untraceable back to their source, they may be non-compliant and any UKCA or CE marks can be considered dubious. Shoddily made adaptors can snap apart when you pull them out of a typical British mains socket, exposing live wires inside. One relative unplugs everything that is not in use, even the smart meter, when she is not at home. A fire officer told her how he attended several house fires a week, all caused by overheating mains adaptors and chargers.

I finally chose a multi-voltage 34W type branded 'Zolt' which offers 3V through to 12V as well as 5V and a USB A-type port, rated up to 2A. This UKCA-labelled adaptor seems well made and also has an LED pilot light and comes with nine DC plug adaptors, including some handy USB types. It's happily powering my router as I write, and the multi-voltage selector makes it an ideal spare to keep in stock. It is hard-wired as centre (tip) positive. At the time of writing, it's available on Amazon (B08L3HD4MR).

This Zolt-branded variable voltage mains adapter has a DC and 5V USB connection kit and carries the assurance of UKCA markings.



DC connectors with bifurcated contacts – recognisable by the slotted centre – offer the best electrical and mechanical contact.

Obviously, a matching DC jack was also needed for the router and users are left to puzzle over several dozen combinations and styles. I saw one 100W 'universal' power brick sold on eBay had nearly 30 such DC adaptors to fit a laptop, and readers doubtless have handfuls of those primitive two-pronged DC plugs kicking around somewhere, though never in the size that you need. In my case I counted at least seven combinations of the commonest 5.0 and 5.5mm (OD) ones, with just fractions of a millimetre to choose between them. Until they invent a DC connector measuring tool, I often end up checking the outer diameter with digital callipers. Getting the correct *innermost* conductor size is more problematic: some plugs are a wobbly fit, and finding the most reliable size takes some trial and error. DC plugs with bifurcated contacts (recognisable with their slotted centres) provide the best grip and electrical connection. Confusingly, they are sometimes specified as having *two* inner diameters – one with their spring contacts open (ie when slack, unsprung), and another when compressed tightly shut (in situ).

More USB gadgetry...

Numerous USB-powered accessories are now sold online through the usual sources. A 5V supply for electronic gear

Linke
RYOBI

Charging solar floodlights from a Ryobi 18V USB adaptor and monitor, with a custom 5V lead and DC connector.

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This USB digital voltmeter/ammeter displays the status of the charging rate. It logs data on ten channels.

can be derived from a USB A-type lead terminated with a suitable DC adaptor plug – kits of these are available online. I use one to charge up solar floodlights from an 18V Ryobi USB adaptor when overcast weather is preventing the solar cells from charging in the daytime. This home-brew 18V USB powerbank is kept in a marine battery box to withstand wintry weather. Sometime, I'll modify the Ryobi adaptor to add an LED power-on pilot light, which is a strange omission, but for now I use a USB LED pilot light on a spare port (see photo) as a reminder.

Many readers own a 10-20,000mAh USB powerbank to top up their mobile phones or tablets. I've found alarming differences in the build quality of USB leads, especially when high-current, fast-charging PD (power delivery) devices are used with them. Some USB connectors become very warm during rapid charging, so I tend to keep a wary eye on powerbanks when in use. An inline USB digital voltmeter/ammeter (available online for a few pounds) allows me to monitor the charging current and capacity. They also have ten memories, scrolled through using a pushbutton. I gave a similar one to the owner of a Samsung tablet which had a slightly wobbly USB jack, so she could tell if it was charging properly when she 'jiggled' the plug!

Last, with the holiday season in mind, here are some useful travel tips: if ever readers find themselves needing to charge up their mobile phone or tablet at a public USB outlet (eg, at an airport, shopping mall or cafe), then a clever USB pass-through adaptor is available that provides power only, with the serial data pins omitted. This claims to overcome the risk of so-called 'juice jacking', where a hacked USB outlet might try to install malware over the USB data bus. The PortaPow Data Blocker adaptor is available from the usual online sources for about £7 each.

PortaPow
Data Blocker

The PortaPow Data Blocker has no data pins and claims to prevent 'juice jacking' if a public USB charging point is used. USB A-type and C-type dongles are available.

When out and about, readers will be aware of the risks of using untrusted wireless hotspots which may eavesdrop, hijack or try to install malware through compromised websites: using a VPN connection to surf the web, check mail or use apps is the safest bet.

Tee Time

It's a fact of life that cheap electronic devices, novelties, gadgets and myriad household items can now be sourced from the Far East with little more than a mouse click. Our series *Low Cost Electronic Modules* exploits the availability of these cheap imported circuit boards that aren't worth the time or effort to make at home. Most readers probably buy online from websites such as Alibaba, AliExpress or Banggood at one time or another, with crumpled little polybags from China dropping through our mailboxes a few weeks later (hopefully).

Some Amazon and eBay sellers are highly geared towards the express shipping of goods that arrive directly from China just a few days later. The practice of 'drop shipping' means that some sellers don't even carry any stock, but simply forward customer orders to an order fulfilment centre or to the manufacturers themselves. Many eBay sellers are based overseas, and their online stores often contain a wacky selection of items of dubious value. Even so, eBay can be a goldmine – the other day a critical spare part for a Panasonic razor arrived from a small Japanese store (complete with an origami gift), delivered by DHL in just a few days – although one must keep an eye on the risk of incurring UK import duty and VAT, see: **https://bit.ly/pe-sep23-tax**

eBay also turned up trumps with some silicone rubber O-rings needed for my solar floodlight's waterproof DC connectors, which came from China and were another welcome little 'find'.

Lately, a new web-based e-commerce brand has arrived in the UK that is gunning for a big slice of the action. Already hugely popular in the US, the Chinese sales platform Temu ('Tee-Moo') has come from nowhere and is setting out to rival Amazon and AliExpress as a consumer-friendly online bazaar that sells a huge range of mostly unbranded little gadgets, gifts, novelties and accessories of the sort that you probably won't mind gambling on buying, in the hope that things won't go wrong. The Temu app is currently the most downloaded one from Apple's store, and Temu's online advertising has reached saturation level: brand recognition is the name of the game for now, and Temu is carving its way relentlessly into the market with crazy loss-leading prices and free shipping.

Temu's web pages remind me of those wacky eBay stores hosted by Chinese traders. Scrolling through them makes you tired and plenty of dark-pattern sales techniques are on show, such as countdown timers, roulette wheel spinners and supposed discounts. Avoid links or vouchers containing 'aff' (affiliate) codes, we're told – these are bogus attempts by others to cash in on your business and won't lead to you enjoying better prices.

Many Temu shoppers will see it as having a bit of fun, but early reviews on Trustpilot (see **https://bit.ly/pe-sep23-tp**) from UK customers are polarised: two thirds of reviewers were delighted, or maybe they're just easily pleased, while one third were very unhappy. One user commented that Temu scrapes up huge amounts of personal data while others complain of being bombarded with notifications and marketing after signing up with Temu, the pressure to buy being incessant. You can sign up at **temu.com** if you want to try those early discounts, though one reviewer cautions buyers to 'probably steer clear of some electrical items'. That likely includes unbranded mains adaptors.

It's here... somewhere! Using smart meters in isolated rural properties may be impossible, so traditional meters will still have to be read manually.

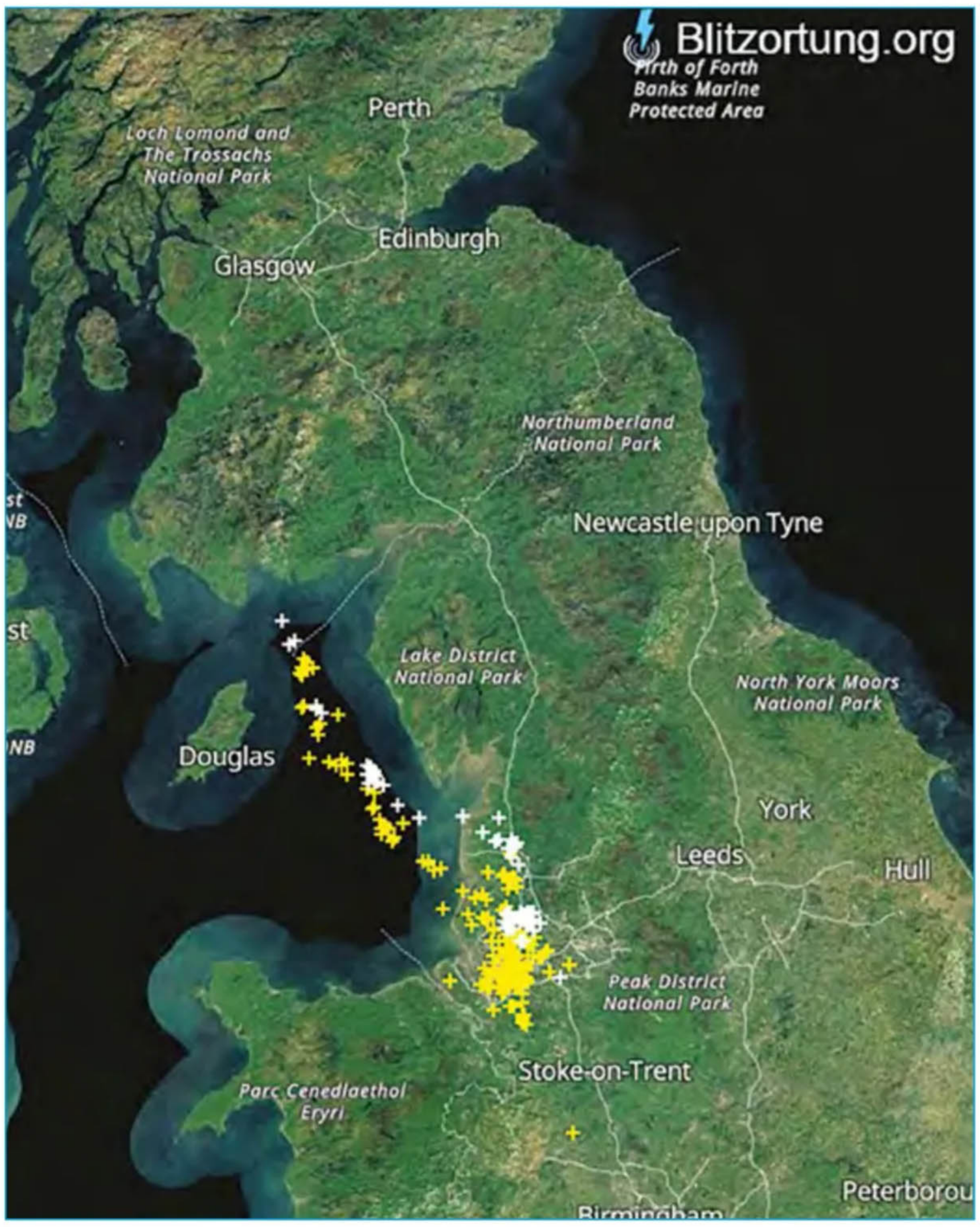
Down on the farm

Regular readers will recall my recent piece about shopping online for house insurance on behalf of an elderly lady who lives in a remote farm. This week, your scribe was down on the farm again, this time waist high in a field of hay, in search of the farm's electricity meters. It turned out that meter readings were being submitted monthly over the phone (there's no Internet access, remember) but errors that had accumulated over time meant the monthly bill was out of kilter and the owner was owed a very substantial refund. I have nothing but praise for the electricity supplier, E-On, who went to great lengths to rectify matters after I explained and submitted accurate readings (and emailed them a photo of the meters just to be sure). E-On helpfully suggested that I become an authorised user for the lady's account, allowing me to submit readings and print off monthly invoices via the web, something that will be a regular job from now on. Just to remind everyone of the continuing need for cash, the lady then likes to journey to the local post office to pay the electricity bill (and others) over the counter using proper money.

The cost of the UK's bungled smart meter programme is expected to reach £13bn or more, a sum equal to nearly a quarter of the UK's entire annual defence budget. The farm would be an ideal application for a smart meter, and one was in fact ordered last year. However, the visiting engineer took one look at the field and beat a hasty retreat, claiming that fitting one was impossible. Furthermore, the farmhouse was too far away from the electricity meters anyway, as the maximum recommended distance between a smart meter and an In-Home Display is just 10m. The Data Communications Company (DCC) – the name behind Britain's smart meter rollout – boasts that the [smart meter] network now 'supports almost 25 million meters in 15 million homes, and is becoming one of the most far-reaching communications technologies in the country', but it seems it won't ever reach the farmhouse nor its meters located 50m away in a field full of hay. Thus, I have another job for life!

From Bard to Worse

Microsoft's Bing search engine now offers a 'chatty' style of working based on ChatGPT which I find makes a pleasant change from the usual mindless Google searches. Microsoft Windows is also expected to incorporate a humanoid chatbot Help system in future software releases. Meantime, Google is developing Google Bard, an experimental AI chatbot designed to write creative content and answer questions 'thoughtfully'. I asked Bard who Alan Winstanley was and, after thinking about it, Bard replied that 'Alan Winstanley is... the Online Editor of the UK's *Practical Electronics Magazine*, and has written electronics tutorials and magazine features since the 1970s.' Nice to be reminded. But Bard then blew it by adding that 'Winstanley is a regular speaker at electronics events, and is a member of the British Electronics Association. He is also a Fellow of the Institution of Engineering and Technology.' Sadly, I'm none of those things! Try it out at: **https://bard.google.com**


Blitzortung.org
Firth of Forth Banks Marine Protected Area
Loch Lomond and The Trossachs National Park
Perth
Edinburgh
Glasgow
Northumberland National Park
Newcastle upon Tyne
Lake District National Park
North York Moors National Park
Douglas
York
Leeds
Hull
Peak District National Park
Stoke-on-Trent
Parc Cenedlaethol Eryri
Birmingham
Peterborou

The blitzortung.org website shows near real-time progress of thunderstorms all around the world.

In other news, the European Space Agency (ESA) successfully launched the last mission of its Ariane 5 heavy lifter on 5 July – ESA was keen to boast of its 'Franco-German success', transporting two satellites into space for the French and German governments. Nearly 120 Ariane 5 rockets have been launched in total, and previous missions included launching LEO satellites for OneWeb as well as the James Webb Space Telescope. ESA also previously

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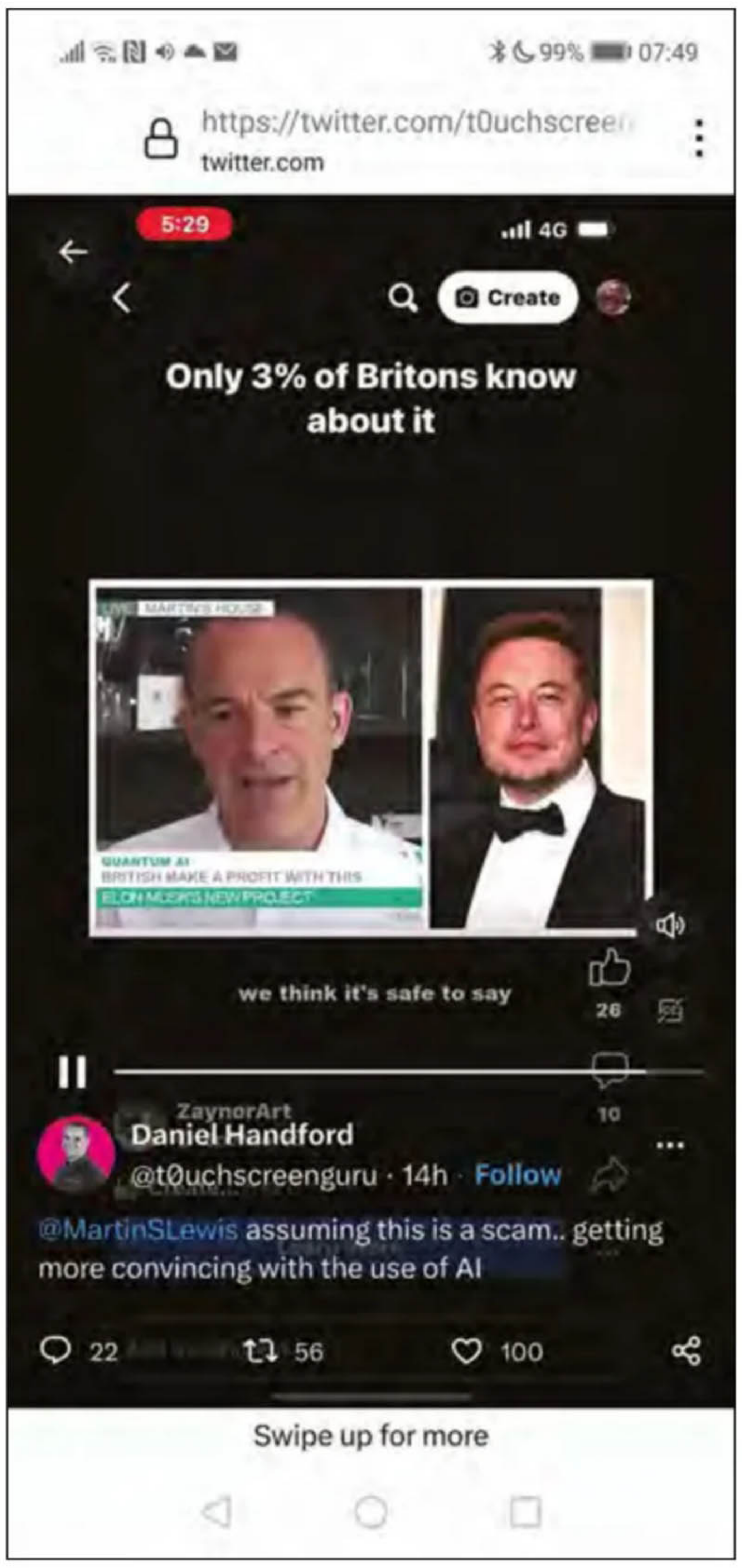
Artist's view of the configuration of Ariane 6 using four boosters. It will be ESA's next heavy-lift vehicle.

used Soyuz rocket launchers until the Ukraine invasion torpedoed all co-operation with Russia's Roscosmos; the same problem caused a set-back for OneWeb's launch schedule.



Only 3% of Britons know about it

we think it's safe to say

Daniel Handford
@t0uchscreenguru · 14h · Follow

@MartinSLewis assuming this is a scam.. getting more convincing with the use of AI

This extremely convincing deep-fake movie impersonates UK consumer champion Martin Lewis promoting phony investments.

Now ESA's focus is on the forthcoming Ariane 6, which will launch from French Guiana and will use either two or four boosters depending on the payload. Interested readers can learn more about Ariane 6 at: **https://bit.ly/pe-sep23-esa**

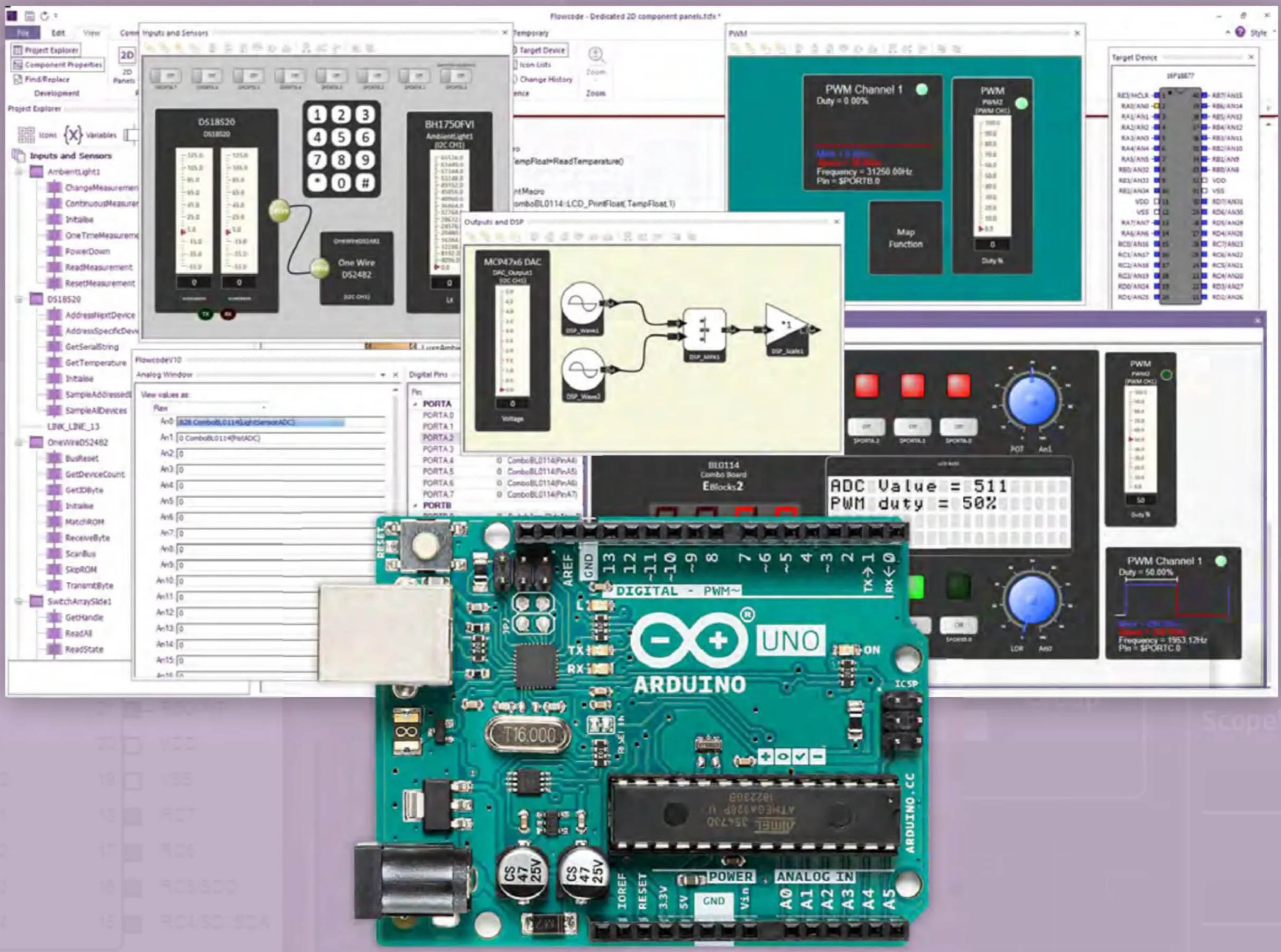
I'm enjoying using my Ecowitt network-enabled weather station which displays readings and statistics from the last 72 hours on a 7-inch TFT colour LCD display (*Net Work*, July 2023). The Ecowitt HP2551 can read data from up to eight 868MHz (in the UK) outdoor wireless sensors, and they have a range of 100m. I've had no problems at all receiving wireless data from the remote sensor array. I've now got my sights on adding a lightning sensor, which detects and counts lightning strikes in the area (the website **https://map.blitzortung.org** is handy for showing the progress of live thunderstorms online). The Ecowitt range is available from Amazon, but do benchmark prices carefully as these vary hugely over time. I've added lots of screenshots showing typical displays on my July 2023 *Net Work* summary blog at: **https://bit.ly/pe-sep23-blog**

Next, news of the TP-Link Tapo smart devices that I'm trying at home (see *Net Work*, December 2022). One Tapo smart bulb has already been replaced under warranty, though the cost of return postage made it barely worth doing. I find the Alexa skill integration works maybe 85% of the time, possibly due to bottlenecks in Amazon's cloud: sometimes a Tapo smart bulb or socket won't respond for up to 10-20 seconds, if at all, leaving me guessing what's going to happen next. The Tapo app is the only other means of controlling it, always assuming I have my smartphone with me. To be fair, Tapo is a low-cost consumer range of smart devices, and in my experience it's alright as far as it goes, but personally I wouldn't feel confident in trusting it to control anything other than basic non-essential loads like lighting or audio gear.

Regular web users will recognise scam adverts when they see them, but a new and deeply worrying trend is emerging that involves deep-fake videos of well-known presenters promoting bogus financial services. A deep-fake movie showing Martin Lewis, the popular UK consumer campaigner, talking about Elon Musk's supposed new 'investment project' for UK investors is utterly convincing. Lewis is pushing hard to have scam ads like these banned because, in his words, people will lose money and they will ruin lives. Maybe alert your friends and family about them – a clip can be seen at: **https://bit.ly/pe-sep23-scam**

Finally, this month, more than 1,000 LED drones were used by Sky Elements in a Guinness world-record display to celebrate the 4 July in Texas. The display showcased milestone events in American history in the night-time skies and extracts of the colourful show can be seen on a YouTube movie at: **https://bit.ly/pe-sep23-led**

The author can be reached at: alan@epemag.net


ADC Value = 511
PWM duty = 50%
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Geoff Graham's

GPS-SYNCHRONISED ANALOGUE CLOCK WITH LONG BATTERY LIFE

ADJUST
G65
22pF
BAT85

This GPS Clock Driver converts an ordinary wall clock into a highly accurate timepiece that will keep exact time (within seconds) for up to eight years using a pair of C cells. You need not touch the clock during that period; it will automatically adjust for daylight saving by adding and subtracting an hour exactly when needed. This is a clock you can rely on to tell you the correct time.

It is amazing how useful it is to have at least one highly accurate clock in the house. At a glance, you know the correct time without having to remember if that clock is running slow or fast and by how much.

Most people would be happy with a wall clock that was accurate to the minute, but with this project, it will be accurate within a few seconds. Even better, any inaccuracy will not accumulate – the clock will remain that accurate for the life of its battery.

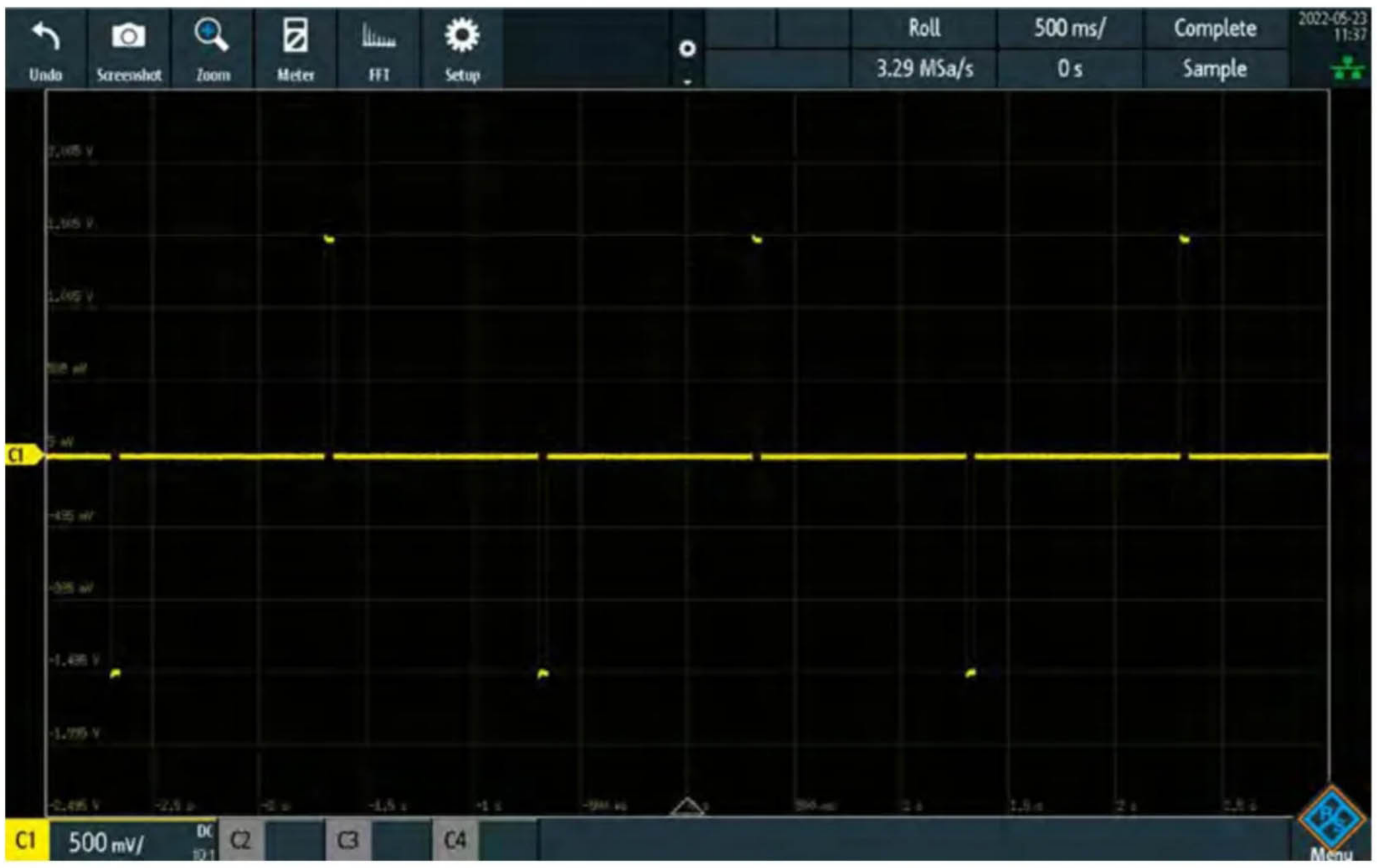
Adjusting for daylight saving is an annoyance with traditional quartz wall clocks. Twice a year, it forces you to get up on a chair or step stool to take down the clock and adjust its hands. Our GPS Driver automatically makes those adjustments for you.

At 2am on the day specified for the start of daylight saving, the clock will begin running fast until it has added the required hour. Then, at 3am on the day specified as the end of daylight saving, the clock will run slow or stop until it has returned to the non-daylight saving time.

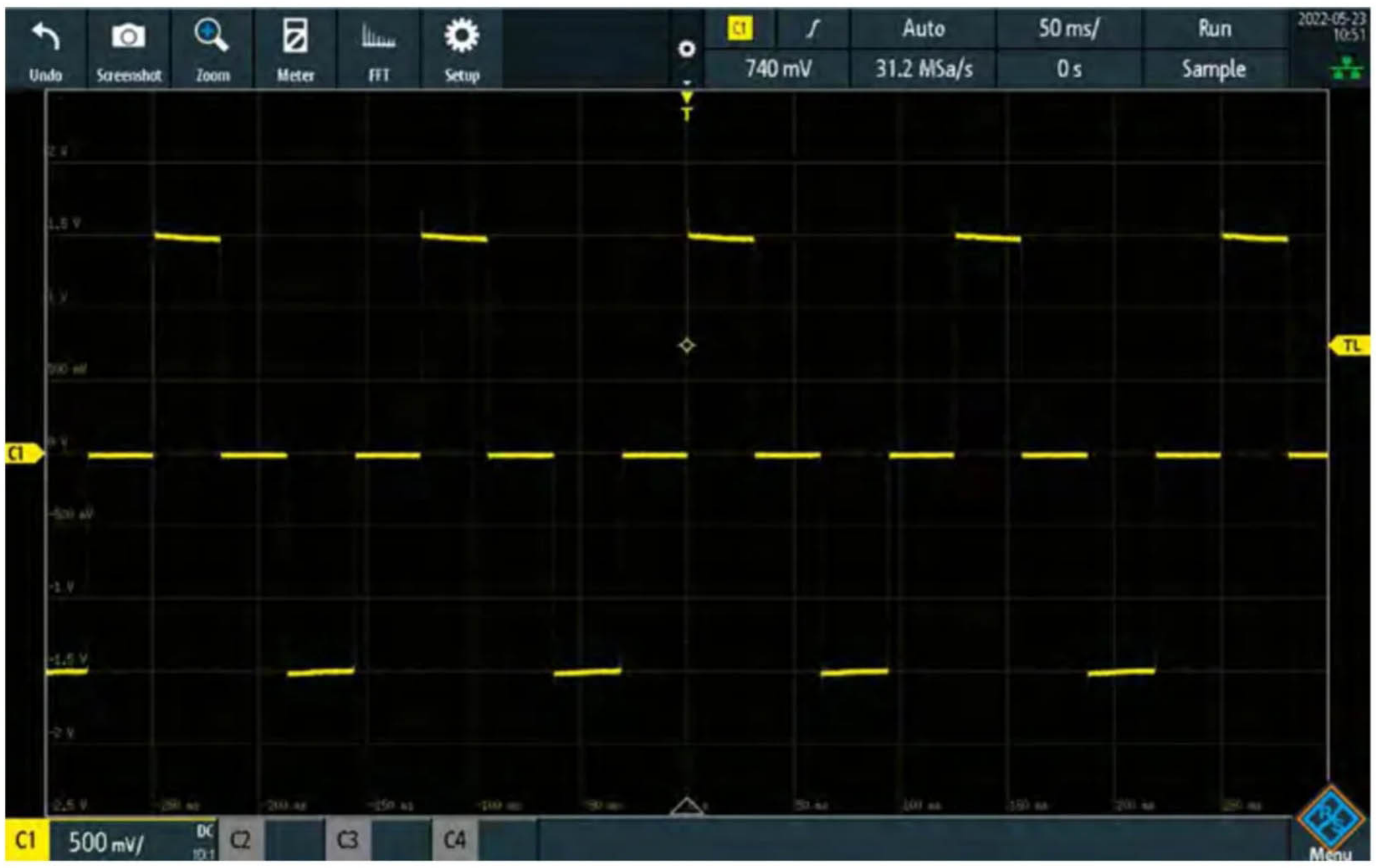
This is accomplished using a GPS module to get the precise time from the network of GPS satellites and some clever software to control the clock's hands.

We have published similar designs many years ago (the last was in *PE*, February 2018), but they all had a relatively short battery life. By using ultra-low-power components and some extra tricks in the firmware, this design will run for about two years on a pair of AA cells and up to eight years with C cells.

It will work with most wall clocks on the market. All that is needed is a modification to connect wires to the stepper motor in the clock's movement. Luckily, that is usually easy.



Scope 1: the output of the GPS Clock Driver for a stepping movement consists of alternating positive and negative pulses that drive the rotor in the clock's motor to make a 180° step with each pulse. Each pulse is about 40ms in duration, and they are delivered once per second.



Scope 2: the output driving a sweep movement; a continuous stream of positive and negative pulses at 8Hz. Each pulse is 31.25ms long with 31.25ms between pulses, resulting in 16 pulses per second. At low battery voltages, the clock driver lengthens the pulse time by 24% and reduces the idle time by the same amount, delivering more energy to the clock's motor.

Stepping clocks

There are two types of analogue wall clocks: stepping clocks, where the second hand steps once a second, and sweep clocks, where the second hand moves smoothly around the dial. Stepping clocks are more common than sweep types. They have a Lavet-type stepping motor consisting of a small magnet that rotates between a coil's magnetic poles.

The clock driver delivers alternating positive and negative pulses to this coil, and the rotor rotates 180° with each pulse. These pulses are about 40ms in duration, and one is delivered per second (as shown in Scope 1), causing the second hand to advance once per second.

Stepping clocks vary considerably in quality and price. We purchased an example for testing from a budget store for a couple of quid, and while it was not the best, it was also not the worst clock movement. Its accuracy was terrible but, as we are replacing its driving circuit with our own, that doesn't matter.

Typically, stepping clock movements have a coil resistance between 200Ω and 500Ω, with a higher resistance indicating a longer battery life (the budget special was 375Ω).

Sweep clocks

The alternative sweep clock movements, sometimes called 'silent' or 'continuous' movements, have a similar drive motor except that it is driven by a continuous stream of positive and negative pulses at 8Hz, as shown in Scope 2. This continuously spins the rotor, with its momentum keeping it moving between each pulse, so it does not make individual steps like the stepping type movement.

As a result, the second hand moves continuously (sweeps) around the dial, and the clock is near silent. This contrasts with the stepping types, which make an audible tick sound every second.

Each 'sweep' pulse is 31.25ms in duration with a dwell time of 31.25ms between pulses, resulting in 16 pulses per second. Because the motor is drawing current 50% of the time, you would expect the battery to be flattened in no time compared to a stepping clock. Sweep movements avoid this by using a coil with many more turns and a higher resistance (typically 5kΩ).

Einstein's theory of relativity and GPS accuracy

GPS satellites circle the Earth at an altitude of 20,000km and are used at 'trilateration' locations using precise onboard clocks. In their high-altitude orbits, the clocks experience a weaker gravitational field, so spacetime is warped differently for them compared to clocks on Earth. The effect is that the clocks speed up at a rate of 45μs/day.

The satellites are also whizzing around at pretty high speeds (about 14,000km/h), and the time dilation predicted by Einstein's special theory amounts to slowing the clocks by 7μs/day. Together, these effects amount to a net speeding up of 38μs/day.

That doesn't sound like much, but ignoring it would lead to a vast inaccuracy in the global positioning system within a few hours. Light travels over 10km in 38μs, and that sort of error in position per day would not make for accurate navigation.

The solution is to slow the satellite clocks by a precise amount calculated using Einstein's theory of relativity so that they match time measured on the Earth's surface. This allows the system to work to accuracies of metres rather than kilometres.

Edited excerpt from 'Why does E=mc^2' by Brian Cox and Jeff Forshaw, ISBN 978-0-306-81758-8

Sweep clocks are more expensive, typically £30 to £80 (and up). However, we found an excellent example at IKEA (called 'TJALLA') for just £9, and it performed pretty well, rivalling a genuine Seiko sweep movement that we purchased for around £17.50. The only problem with the IKEA movement was that it was difficult to pull apart to modify– and even harder to reassemble.

Keeping perfect time

When the clock is running, the GPS Clock Driver will need to occasionally add or subtract a second to keep the hands accurate. This is easy for a stepping movement; the Driver delivers two pulses in one second to advance the clock by one second, or no pulses for a second to retard it by one second.

With daylight saving, this is more noticeable. When daylight saving starts, the hands need to advance by one hour and to do this, the Driver generates two steps every second for an hour until the hands have reached the correct daylight saving time. At the end of daylight saving, the clock will stop stepping for an hour until the time catches up with the position of the hands.

Sweep movements need a different approach because we must maintain the momentum of the spinning rotor; it cannot simply go twice as fast or stop/start. So, the adjustment must be more subtle. To add or subtract a second, the movement is run 12.5% faster or slower for eight seconds.

With daylight saving, this means that it will take eight hours to add the required hour and a similar time to retard by an hour. While this is a long time for the clock to be catching up, it only happens twice a year. Instead, you could disable daylight saving in the setup and manually adjust the hands when required.

How the Clock Driver works

Fig.1 shows the GPS Clock Driver block diagram. Microcontroller IC1 generates a sequence of positive and negative pulses that are buffered by op amp IC2. IC2 drives the motor in the clock movement.

A crystal oscillator running at 32768Hz (2^{15}) drives a 16-bit counter/timer in IC1 to generate the precise timing required. Importantly, this timer can operate while the microcontroller's core is in sleep mode, so it only consumes a few microamps.

The microcontroller spends most of its time in this low-power sleep mode. When it is time to generate an output pulse, the timer wakes the CPU to drive the output pin to start the pulse, and it resets the timer to wake again when the pulse is due to finish. When it wakes again, it terminates the output pulse, sets the timer for the next pulse and goes back to sleep.

This continues forever, with the microcontroller jumping in and out of sleep and toggling the output pin to generate the pulse train for the clock's motor. The CPU's running time is short compared to the sleep time, so the average current drawn by the micro is very low.

The sequence of pulses to the clock's motor alternate between positive and negative, with a dwell time in between. This is achieved by switching the pin between high, low and high-impedance.

Op amp IC2 buffers this signal to drive the clock by bringing its output to the positive terminal of the upper cell or the negative terminal of the lower cell, or the junction for the dwell time between pulses. This divides the load between the cells, with each providing half the power for the clock motor.

GPS synchronisation

Not shown in Fig.1 is the boost voltage regulator that powers the GPS module. Occasionally, after delivering a pulse to the motor, the firmware will not put the CPU to sleep but will keep running and enable the boost regulator, which delivers a regulated 4V to the GPS module. It will then get an accurate time from the constellation of GPS satellites.

Generally, it takes less than a minute for the GPS module to locate sufficient satellites and return the precise time. When the microcontroller has received this time, it shuts down the regulator

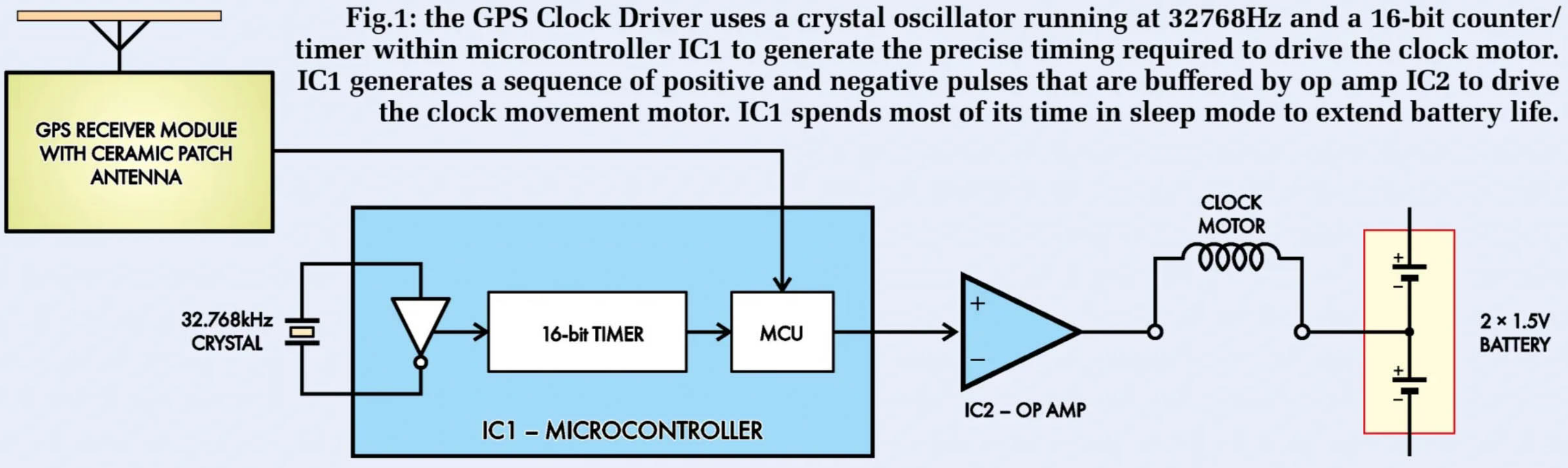


Fig.1: the GPS Clock Driver uses a crystal oscillator running at 32768Hz and a 16-bit counter/timer within microcontroller IC1 to generate the precise timing required to drive the clock motor. IC1 generates a sequence of positive and negative pulses that are buffered by op amp IC2 to drive the clock movement motor. IC1 spends most of its time in sleep mode to extend battery life.

and makes some calculations to determine any timekeeping errors. After this, it reverts to its regular strategy of sleeping until the next pulse is due.

Initially, the time between GPS synchronisations is set to 12 hours, but over time the firmware will increase this to five days. The average battery power required for GPS synchronisation is minimal, so this process does not materially affect the battery life.

The firmware keeps track of the position of the clock's hands as the number of seconds since 1 January 2000. The GPS time is also converted to this format, so it is easy for the firmware to compare the two and calculate any correction that may be required.

The difference between the two numbers represents the error in the 32768Hz crystal oscillator, which is used to keep the time between GPS synchronisations. By working out this error, the firmware can correct for it over the next period between GPS synchronisations by occasionally adding or skipping a second as needed.

This will start working following the second GPS synchronisation and will keep the clock accurate regardless of any error in the crystal, including compensating for additional errors due to temperature and ageing of the crystal. The practical effect is that, apart from the first day, the clock's hands will always be accurate within a few seconds between GPS synchronisations.

Also, the next GPS synchronisation should not need a large correction; maybe only a second or two (or possibly none).

When the boost regulator and the GPS module are initially powered, they can draw a lot of current, especially if the cell voltages are low. This cannot be sustained by a battery on its last legs, so the firmware measures the battery voltage when running the boost regulator. If it is below 2.25V (1.125V per cell), it will skip any subsequent GPS synchronisations.

This will have little effect on the clock's accuracy as it will only occur towards the end of the battery's life, and by then, the firmware will have a good idea of any error in the crystal and will continue to compensate for it.

Circuit details

The full circuit, shown in Fig.2, is based around a Microchip PIC16LF1455 microcontroller. It is an extra-low-power device that can operate with a supply voltage as low as 1.8V (0.9V per cell in this case). Most clock movements will stop running between 0.9V and 1.0V per cell, so the microcontroller will run for as long as the clock's motor can keep going.

This microcontroller also has USB support, so a mini Type-B socket is provided for configuration (CON4). When a host is connected or removed, the microcontroller will detect the USB +5V voltage on its pin 9.

The 5V is dropped to 2V by the 10kΩ/6.8kΩ resistive divider, so it will not damage the microcontroller when the battery is at 1.8V. It will still be recognised as a high logic level when the microcontroller runs from a fresh battery (3.2V).

Any change in the voltage on pin 9 will cause the microcontroller to restart. If, upon restarting, the USB voltage is present, the firmware will set the microcontroller's clock speed to 16MHz and enable the USB interface. LED1 will flash three times to indicate that the firmware is in configuration mode.

If the USB voltage is not detected on startup, the clock speed will be set to 4MHz, and the USB controller will be disabled (both to save power). The firmware will go through the usual clock startup routine, flashing LED1 twice.

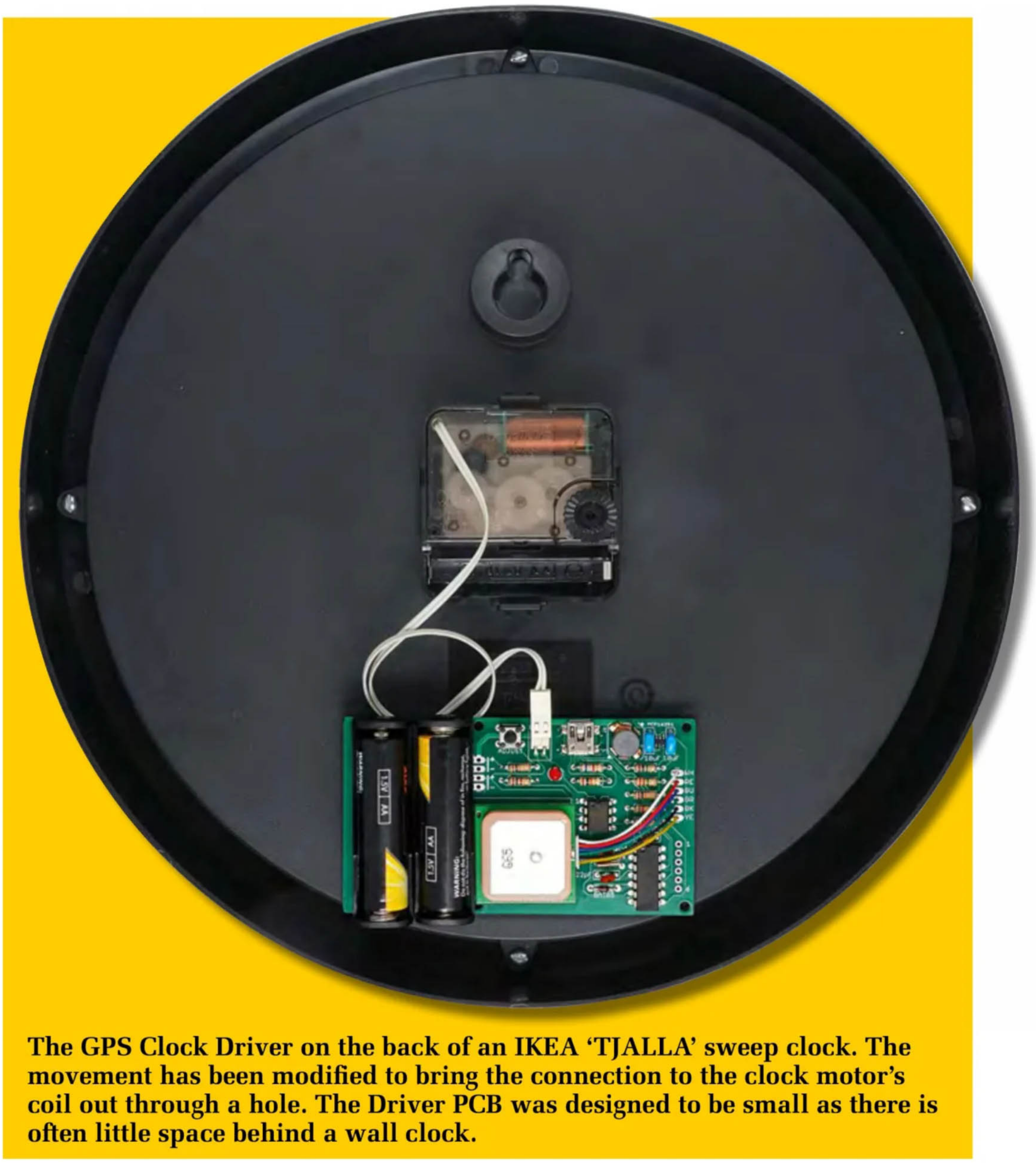
The PIC16LF1455 has an unusual feature: it can use the host's USB signalling rate to fine-tune its internal clock. The USB specification requires a high accuracy in this timing and that generally requires a 12MHz, or similar, crystal oscillator. But the PIC16LF1455 does not need this, which frees up two pins and makes for an easy-to-implement USB interface.

The microcontroller steps the clock movement by driving its pin 8 high for a negative pulse, low for a positive pulse or setting it to high impedance for the idle time between pulses. This controls op amp IC2 (MCP6041), which uses the centre point of the two cells as its reference and drives its output either positive or negative relative to that.

The MCP6041 has several desirable characteristics: its output will swing rail-to-rail, which means that little of the precious battery voltage is lost within the op amp. It also has an extremely low quiescent current (less than a microamp), so the battery is conserved between pulses, and it will operate at a supply voltage well below 1.8V (0.9V per cell).

Boost regulator

When the microcontroller needs to get the GPS time, it drives its pin 7 high, enabling boost regulator IC3,



The GPS Clock Driver on the back of an IKEA 'TJALLA' sweep clock. The movement has been modified to bring the connection to the clock motor's coil out through a hole. The Driver PCB was designed to be small as there is often little space behind a wall clock.

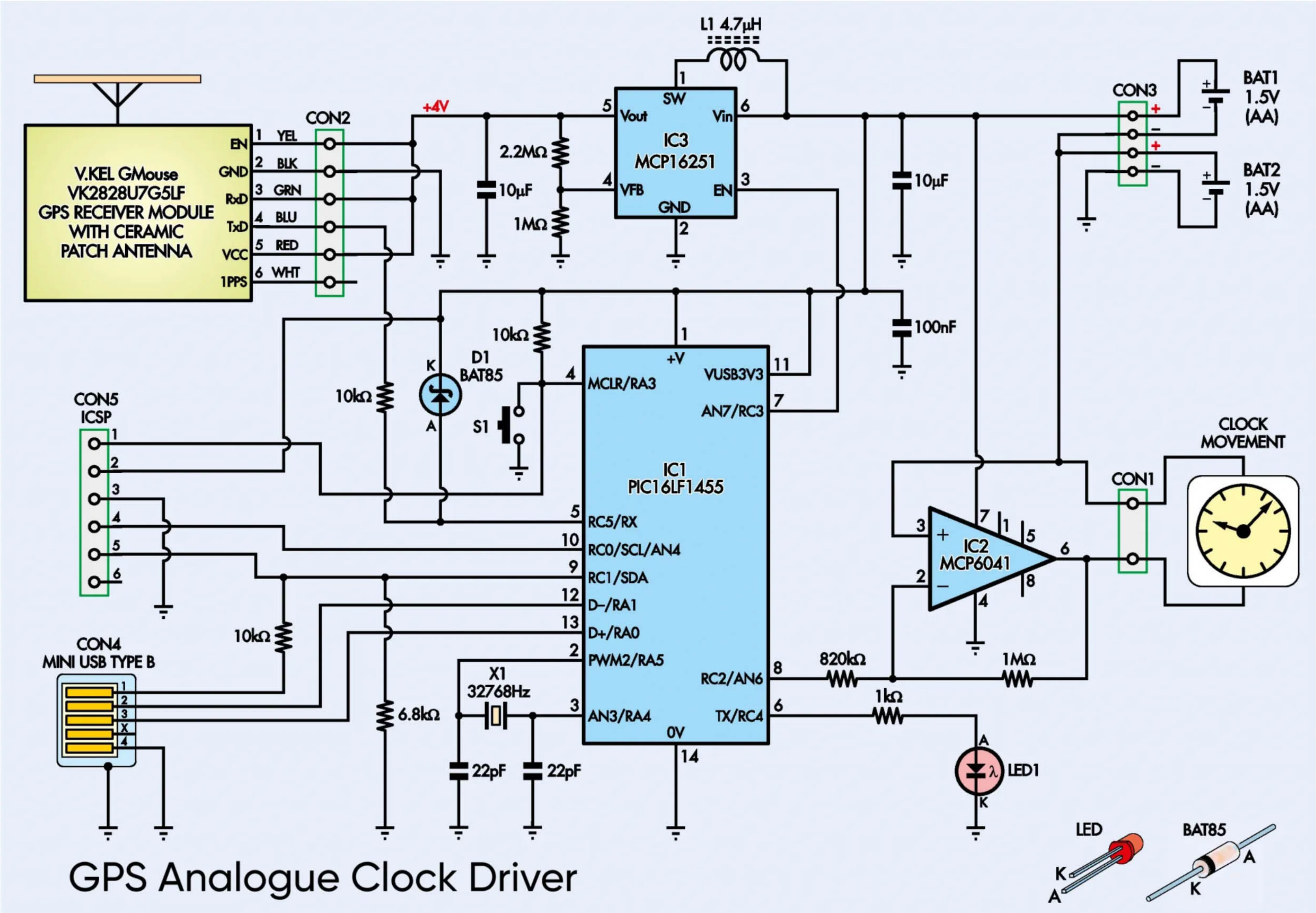

L1 4.7µH
SW
Vout
Vin
IC3
MCP16251
VFB
EN
GND
+4V
2.2MΩ
1MΩ
10µF
10µF
100nF
CON2
EN
GND
RxD
TxD
VCC
1PPS
YEL
BLK
GRN
BLU
RED
WHT
V.KEL GMouse
VK2828U7G5LF
GPS RECEIVER MODULE
WITH CERAMIC
PATCH ANTENNA
CON3
BAT1
1.5V
(AA)
BAT2
1.5V
(AA)
10kΩ
D1
BAT85
K
A
S1
10kΩ
CON5
ICSP
+V
MCLR/RA3
VUSB3V3
AN7/RC3
IC1
PIC16LF1455
RC5/RX
RC0/SCL/AN4
RC1/SDA
D–/RA1
D+/RA0
PWM2/RA5
AN3/RA4
RC2/AN6
TX/RC4
0V
10kΩ
CON4
MINI USB TYPE B
X1
32768Hz
22pF
22pF
6.8kΩ
820kΩ
1MΩ
1kΩ
LED1
IC2
MCP6041
CON1
CLOCK
MOVEMENT
LED
BAT85
GPS Analogue Clock Driver

Fig.2: the Microchip PIC16LF1455 microcontroller (IC1) runs the show. It steps the clock movement by driving its pin 8 high for a negative pulse, low for a positive pulse or setting it to high impedance during the idle time between pulses. Op amp IC2 buffers this signal and uses the centre point of the two batteries as its reference to drive its output either positive or negative. When the microcontroller needs to get the GPS time, it drives its pin 7 high, causing the boost regulator (IC3) to start running and power the GPS module.

a Microchip MCP16251. It generates about 4V at its pin 5. This is set by the ratio of the 2.2MΩ and 1MΩ resistors; 4V was chosen so that the regulator will have some headroom to regulate the output voltage with fresh cells.

The MCP16251 disconnects its output when it is disabled by a low voltage on its pin 3. This is unusual in a boost regulator, and is an important characteristic as it prevents the GPS module from draining the battery when it is not being used.

The output from the GPS module (VK2828U7G5LF) is a standard asynchronous serial stream at 9600 baud with TTL signalling voltages. To protect the microcontroller when the battery voltage is low, BAT85 diode D1 clips its output to just a little over the battery voltage.

The module comes with a connector and colour-coded flying leads, as shown in Fig.2. It also has two indicator LEDs; the red LED, which indicates power, while the green LED will flash at one pulse per second.

Battery life

The main factors determining how long the batteries will last are the current drawn by the clock's motor and the quality of the cells used.

Our budget stepping clock drew an average of 170µA while the IKEA sweep clock averaged 135µA (both with a drive signal of 1.5V peak-to-peak), typical of these types of movements. Because the GPS Clock Driver powers the motor from both cells, the typical average current drawn from each is 70-85µA.

The average current drawn by the microcontroller is about 18µA, which applies to both cells. The shutdown current of the boost regulator and a few other sources add about another 3µA per cell.

Finally, there is the current consumed by the periodic operation of the GPS module. The peak current is up to 100mA, but it is only drawn for a short period every five days, so its long-term average is quite low at about 5µA.

Adding all of this together means that a typical clock will draw about 100µA from each cell.

To keep the clock running for longer on low battery voltages, the firmware changes the pulse train duty cycle if the battery voltage is less than 1.125V per cell. It lengthens the pulse time by 24% and reduces the idle period by the same amount. The waveform's frequency is the same, so it does not affect the timekeeping accuracy, but it delivers more energy to prevent it from stalling.

This allows a sweep clock to continue operating below 1V per cell, thereby using the last drop of energy in the cell and lengthening the running time. The effect on a stepping clock is not as significant, but most will last until 1V is reached.

By the way, if you are testing the minimum running voltage for your clock, you need to mount it in a vertical position. The effort required to raise the second hand against gravity will cause the clock to stop early compared to if it is mounted horizontally.

Also, if you are not concerned with having a second hand, you can remove it, and the clock should run for a few weeks longer because it does not have to put in that additional effort.

Good-quality alkaline AA cells have a capacity of 2000mAh or more with light loads (terminating at 1.0V) so, with a total current draw of

100µA, you could reasonably expect the battery to last about two years. Obviously, this can vary considerably depending on the quality of the movement and the cells, but it is a reasonable estimate.

If there is room behind the clock, you could separately mount two C cells which have a capacity about four times that of the AA cell, so you could expect up to eight years of operation (see below). The limiting factor would be the quality of the cells and their rate of internal self-discharge.

Programming and sourcing the parts

You will need to program the microcontroller yourself. There are six solder pads on the PCB for mounting a pin header. This enables you to program the chip in-circuit – you just install the header and connect a PIC programmer such as a PICkit 3 or PICkit 4.

The firmware is available from the September 2023 page of the *PE* website at: **https://bit.ly/pe-downloads**

You can also access the firmware from: **http://geoffg.net/gpsclockdriver.html**

It is worth checking **http://geoffg.net** for updates from time to time, as there is the possibility that a bug will be found and fixed.

Besides the PCB and microcontroller, the other project components are standard and can be purchased from the usual suppliers.

Do not substitute the BAT85 diode with another type. It is a schottky type for a low voltage drop, but it also has a low reverse leakage, which is needed to extend the battery life.

We have specified the V.KEL VK2828U7G5LF GPS receiver, a great performer that is readily available at a good price. If you want to use another module, that will probably be OK. Just make sure it uses TTL signalling and not RS-232 levels.

The project's firmware will automatically try the typical communication speeds used by these modules (4800, 9600 or 19,200 baud). It uses the NMEA RMC message generated by the GPS module, which is standard across all manufacturers.

When purchasing the clock, you could choose a clock design that is attractive but swap out the movement for something else. Most high-end clock manufacturers have standardised the physical dimensions of the clock movement and its mounting arrangement. However, this does not apply to cheap clocks, which do not follow any standard.

You can also buy movements online with a wide variety of matching hands. So, making your own clock with a unique clock face is also an option.

Construction

The GPS Clock Driver is built on a 97 × 55.5mm PCB, coded 19109221. It is available from the *PE PCB Service* and is shown in Fig.3. It was kept small as there is often little space behind a wall clock.

You can cut off the end section of the Driver PCB containing two AA cell holders if you want to use separately mounted batteries. That results in a 64.5 × 55mm PCB that should fit almost anywhere.

If cutting the board, do that before fitting any components. Use a metal ruler and a sharp craft knife to deeply score the PCB on both sides deeply, then snap the board apart and tidy up the edge with a file.

The first component to solder is IC3, the MCP16251 in a 6-pin SOT-23 package. It is quite small but not overly difficult with a steady hand. First, determine its orientation. It has a laser-etched dot on the top near pin 1, but it is faint, so it is easier to read the four letters engraved on the chip and use them for orientation.

You will need a x10 or more magnifier to read these letters (some smartphone cameras will do it too). The first two should be 'MB', while the last two can be anything. Pin 1 is at lower left with the letters the right way up.

To solder the chip, first coat the PCB pads with flux paste, then place a tiny solder bump on a corner pad. Position the chip and, while holding it down, apply the iron to that pad.

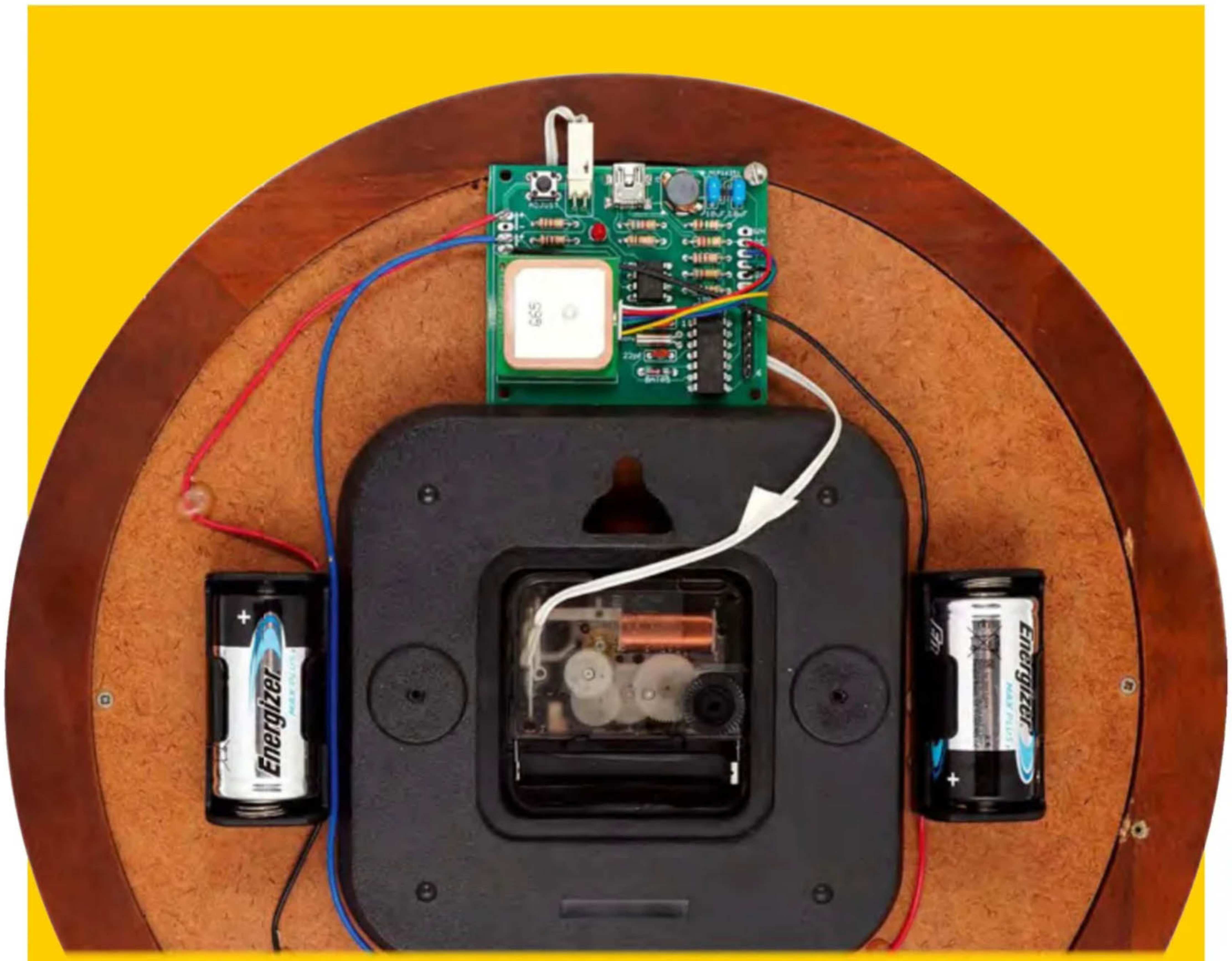
With the first pin tack-soldered and the chip held in position, check and adjust the orientation of the other pins before soldering them. Always apply plenty of flux and use minimal solder on your iron.

Next, fit the USB connector. This has two small plastic posts on the underside that go into two holes in the PCB to position it. Coat the pins and PCB pads with flux gel and, with a small amount of solder on your iron's tip, slide it across the PCB pad to the connector's pins. When the tip of the iron hits the pin, the solder should magically flow around it.

With these small devices, it is easy to create solder bridges between the pins, but they can be removed using solder wick (braid). Finally, check all joints with a powerful magnifier (x10 or x20) to ensure that each joint is correctly soldered with no bridges. Don't forget to solder the larger mounting tabs.

The inductor is the last SMD. Start by placing a small solder bump on one PCB pad, and then, while holding the inductor in place, apply heat to that pad. That should secure it in place. Then, use rosin-cored solder wire to solder the other lug before refreshing the first solder joint.

The remaining components are all through-hole types. Start with the low-profile items like resistors before moving on to higher-profile components such as the LED and cell holders. You can use IC sockets for IC1 and IC2 as these will make removing the device easy if you suspect it is faulty.



A clock using separately mounted C cells for power. C cells have a capacity about four times that of AAs, so a lifetime of up to eight years is possible. However, that will depend on the cells' quality and their internal self-discharge rate. The PCB is much smaller without the onboard cell holders.

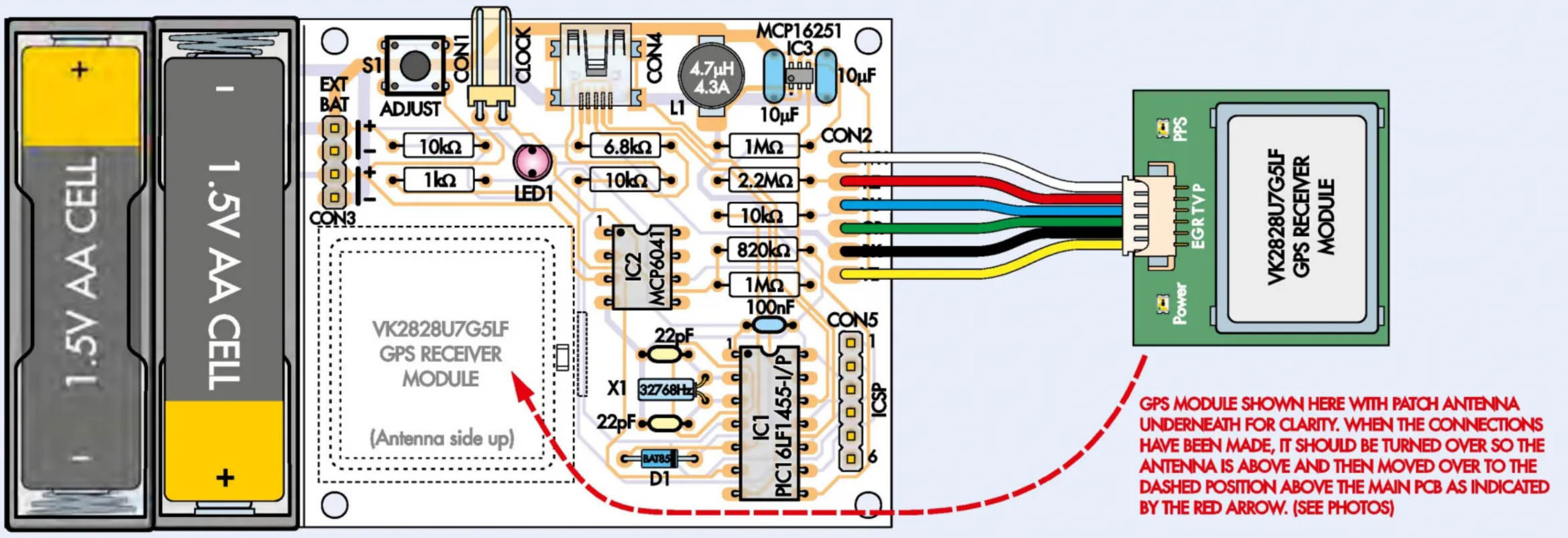

1.5V AA CELL
1.5V AA CELL
EXT BAT
S1
ADJUST
CON1
CLOCK
CON4
MCP16251
IC3
4.7µH 4.3A
L1
10µF
10µF
CON2
10kΩ
1kΩ
LED1
6.8kΩ
10kΩ
1MΩ
2.2MΩ
10kΩ
820kΩ
1MΩ
100nF
CON3
IC2 MCP6041
VK2828U7G5LF GPS RECEIVER MODULE
(Antenna side up)
22pF
X1
32768Hz
22pF
D1
BAT85
IC1 PIC16LF1455-I/P
CON5
ICSP
PPS
EGR TVP
Power
VK2828U7G5LF GPS RECEIVER MODULE
GPS MODULE SHOWN HERE WITH PATCH ANTENNA UNDERNEATH FOR CLARITY. WHEN THE CONNECTIONS HAVE BEEN MADE, IT SHOULD BE TURNED OVER SO THE ANTENNA IS ABOVE AND THEN MOVED OVER TO THE DASHED POSITION ABOVE THE MAIN PCB AS INDICATED BY THE RED ARROW. (SEE PHOTOS)

Fig.3: assembly of the GPS Clock Driver is pretty straightforward. Start by soldering the three SMDs (IC3, L1 and CON4) and check carefully that they all have good solder joints before fitting the through-hole parts. The cell holder polarity is critical, while the LED needs to have its longer anode lead inserted into the pad labelled '+'. The ICs and diode also need to be oriented correctly.

Like the ICs, LED1 and D1 are polarised, so they must be oriented as shown in Fig.3.

The GPS module can be secured to the PCB using double-sided adhesive foam tape. The ceramic antenna should be on top, with the module's metal shield and label against the PCB.

Typically, the antenna should be horizontal and facing the sky for the best sensitivity. If you have the space, you could separately mount the module with the antenna in this orientation. However, our tests showed that the module worked just as well when pointing to the horizon, mounted on the PCB and attached to the back of the clock.

The GPS module is supplied with a connector and colour coded-leads which go to the solder pads on the right-hand side of the PCB. Trim the leads to length and solder them to the respective pads: 'WH' means white, 'RE' red, 'BU' blue and so on.

If using external cells, wire them to the four 'EXT BAT' solder pads. These can be used for terminating soldered leads or a 0.1-inch 4-pin header and socket.

Modifying the clock movement

The idea is to disconnect the clock's stepping motor coil from its control board and connect two flying leads to the coil. All clock movements are different, so we can only give you general guidance here.

The process involves freeing the clock's movement from the clock housing, dismantling it, making the modification and reassembling it.

First, remove the housing holding the front glass of the clock. Generally, this is held in place with screws accessible from the back. Then remove the hands. Generally, the second hand is a friction-fit on a pin in the centre of the shaft, so a gentle pull on this should free it.

Next is the minute hand; in most high-end clocks, it is held down with a circular threaded nut. However, in cheaper clocks, it is often a friction fit on the minute hand shaft. The hour hand is likely a friction fit on the hour hand shaft and should be gently pulled free.

With the hands removed, you will find that the movement is held onto the clock face with a hex nut on the threaded shaft. Remove the nut and it should come free. Some cheaper clocks do not use a securing nut; instead, the movement is held in place by plastic clips on the rear of the clock.

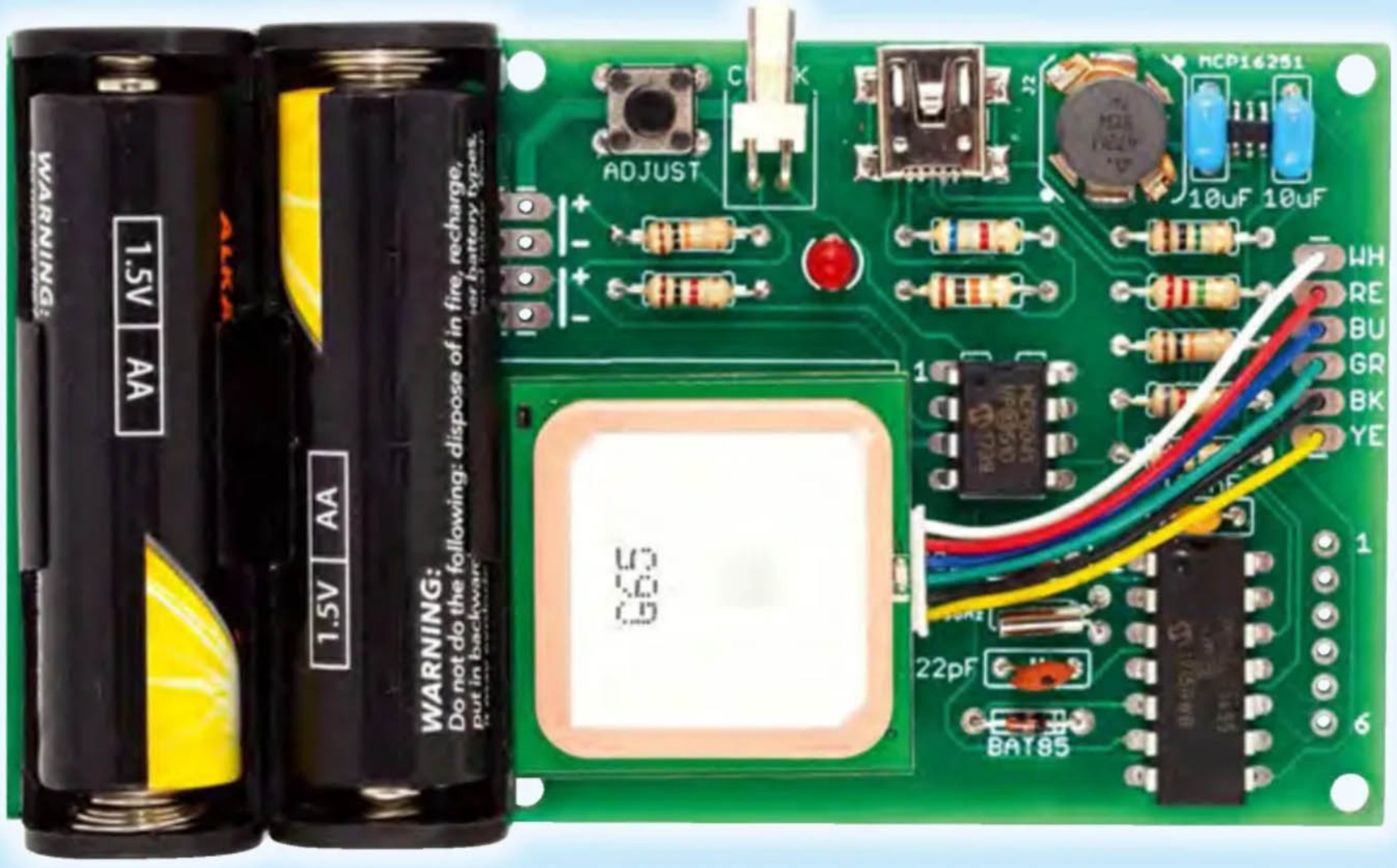
Take photographs of the movement and the layout of the gears before you start dismantling it, then take additional photos as you progress. It is very easy for the gears to fall out while you are handling the movement, and it will then be tough to reassemble it without a guide.

In most cases, the movement will have a top cover held on by clips to the base. You can lever off these clips to remove the cover and gain access to the motor and gears. Inside, you need to identify the motor's coil (this will be obvious) and the wires from the coil, which will be soldered to the PCB with the control chip (normally under a blob of black epoxy).

The wires are very fine, so the best method of disconnecting the control chip is to cut one of the tracks leading from the coil's termination on the control PCB. You can then solder your flying leads to the coil's termination points and feed these out of the movement – you will probably need to drill a hole in the top cover to do this.

Finally, reassemble the clock and terminate the flying leads on a 2.54mm-pitch 2-pin crimp plug.

If you have a stepping movement, you can test your work by connecting a 1.5V AA cell across the leads and reversing it. Every time you reverse the cell, the clock should step by one second.


1.5V AA
1.5V AA
WARNING:
ADJUST
MCP16251
10uF 10uF
WH
RE
BU
GR
BK
YE
22pF
BAT85
1
6

The fully populated Driver PCB. The tactile switch for adjusting the second hand is near the top edge, alongside the USB connector for configuring the firmware. On the far top right are the inductor and other components associated with the boost regulator that provides 4V for the GPS module.

Configuring the Clock Driver

By default, the Clock Driver is set up for a stepping-type movement with no daylight saving compensation. If that is all you need, you can just insert the cells and start the clock running (see 'Powering it up' below). Otherwise, you will need to configure the Driver.

Plug the USB connector into a computer or laptop and insert the cells. The Clock Driver will connect to your computer as an asynchronous serial port over USB, and the LED will flash three times to indicate that the firmware is working in configuration mode. Ensure that fresh cells are installed; partially exhausted cells may not be able to deliver the correct USB signal levels, causing errors.

The Driver imitates the Microchip MCP2200 USB/serial converter. Windows 10 and 11 are delivered with the correct driver installed, but for other operating systems, you may need to load a driver. You can find this on the Microchip website: **www.microchip.com/wwwproducts/en/MCP2200**

You will also need terminal emulator software to send your keystrokes to the clock driver and display anything sent back. For Windows, the sotware we recommended Tera Term is: **http://tera-term.en.lo4d.com**

This is free to download and use. PuTTy is another popular emulator that will also work.

The terminal emulator needs to know the number of the virtual serial port generated when the clock is connected. For Windows, you can find it using Device Manager. Other details such as the baud rate are unimportant and can be ignored.

With everything set up, hit the Enter key on your keyboard, and you should see the configuration header as in Screen 1.

The first question asked by the firmware is 'Sweep (Y/N)'. If you type 'Y' then Enter, you will configure the clock driver for a sweep movement. If you enter 'N' instead, it will be configured for a stepping clock movement.

The next question is 'Use daylight saving (Y/N)', and if you reply 'N', you do not have to do anything else; it will save the settings and you will be prompted to unplug the USB cable. If you replied 'Y', you will need to enter the specifications for the start and end of daylight saving.

Configuring daylight saving

The firmware can cope with the daylight saving requirements for most countries worldwide, although some are just too complicated or vague (for example, Iran's). Table 1 shows the settings required for Australia and New Zealand.

For both the start and the end of daylight saving, you will need to enter three numbers:

1) The month when daylight saving starts/ends (1 to 12 – where 1 represents January).
2) The day of the week when daylight saving starts/ends (with Sunday being day 1).
3) The week of the month it falls in, with 1 being the first week and 4 meaning the last week.

Then you will be asked for your time zone. This should be entered as the number of hours before or after UTC. So, for example, Sydney and Melbourne are +10, Adelaide is +9.5 and Los Angeles is –7.

When you press Enter after that, you will see 'Configuration Saved, Disconnect USB'. Disconnect the USB cable and the clock driver will restart as if the battery has just been connected (ie, it will wait for the next precise half/full hour then start running, as described below). It will remember the settings you have entered, so you never have to re-enter them, even when replacing the cells.

Daylight saving starts at 2:00am and ends at 3:00am. The one exception is the United Kingdom, where it needs to start/end one hour earlier. The firmware determines if the clock is running in the UK by checking the time zone offset, which is zero in the UK.

Powering it up

All you need to do is set the hands to the next half hour or full hour (whichever is closest) and insert the cells, then hang the clock back on the wall. The clock will wait until the next half/full hour is reached and automatically start running. From then on, it will keep precise time until the battery is exhausted.

Do not put cells into the clock's movement. The GPS Clock Driver wholly replaces the controller board inside the movement, so it does not need to be powered.

The onboard LED informs you of the progress during the startup process. When the cells are inserted, the LED flashes twice to indicate that the microcontroller and firmware are running. The firmware then powers up the GPS module, flashing the LED briefly at 1Hz while it is searching for satellites.

When the GPS module has a lock (ie, it has the accurate time), the LED will change to a long flash every second. Finally, when the clock starts running, the LED will turn off.

With a new GPS module, it can take some time (up to 45 minutes) to find enough satellites. That delay might result in the clock starting at the wrong time. So, when you first use the clock, keep an eye on when it gets a satellite lock and readjust the hands if necessary. Once the GPS module has its first lock on the satellites, it is generally much faster, with

Parts List – New GPS-Synchronised Clock

1 double-sided PCB coded 19109221, 97 × 55.5mm available from the *PE PCB Service*
1 V.KEL VK2828U7G5LF GPS module or similar (MOD1)
1 32768Hz watch crystal (X1)
1 4.7µH 4.3A 6×6mm ferrite-cored SMD inductor (L1) **[eg, EPCOS B82464-A4]**
1 4-pin low-profile tactile pushbutton switch (S1) **[Altronics S1120]**
1 2-way 2.54mm polarised right-angle header with plug and pins (CON1)
1 SMD mini type-B USB socket (CON4) **[Altronics P1308]**
1 6-pin header (CON5; **optional**)
2 PCB-mounting single AA cell holders (BAT1, BAT2) **[Altronics S5029]**
1 14-pin DIL IC socket (**optional**)
1 8-pin DIL IC socket (**optional**)

Semiconductors

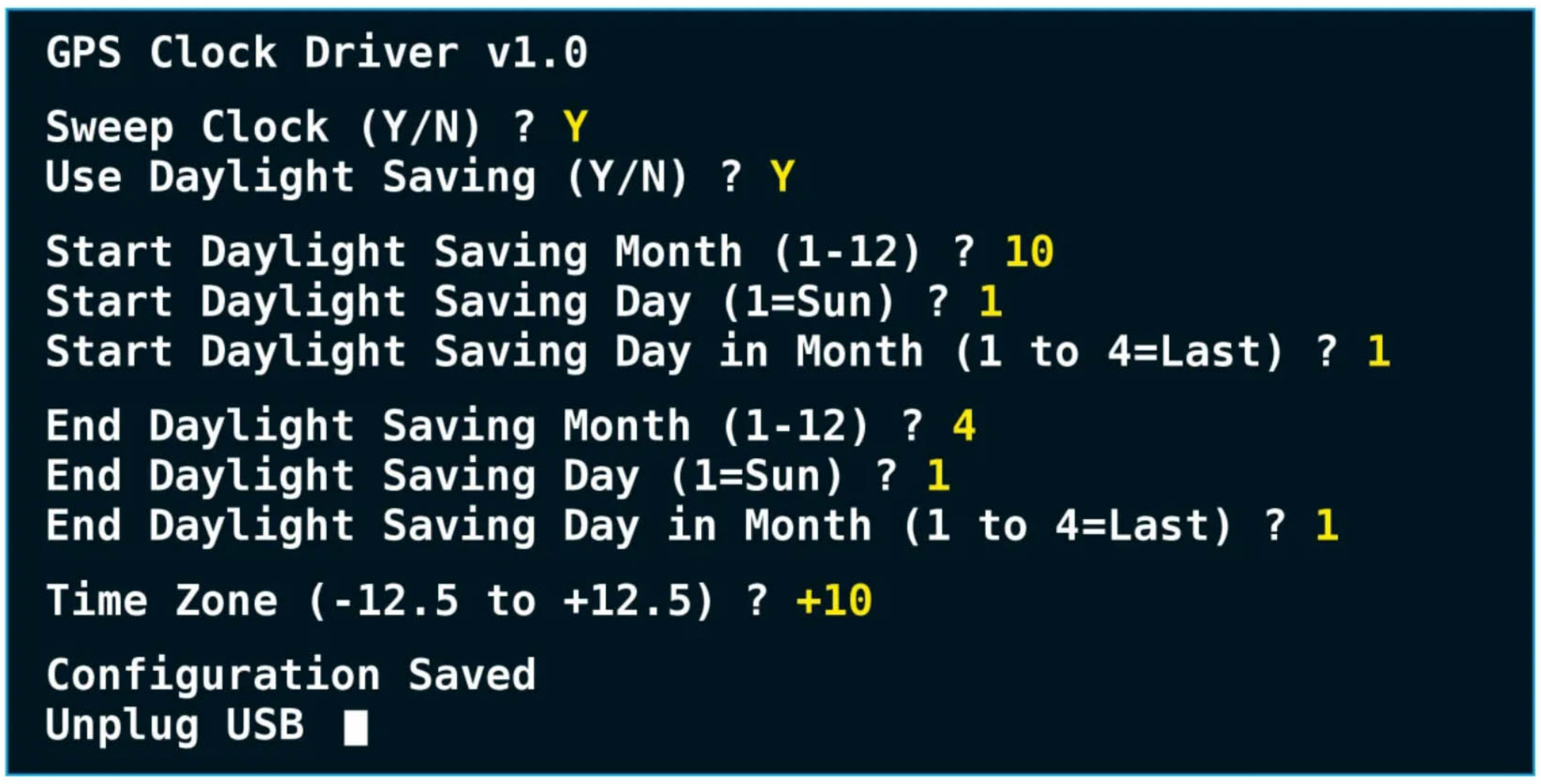
1 PIC16LF1455-I/P microcontroller programmed with 1910922A.HEX, DIP-14 (IC1)
1 MCP6041-I/P 600nA rail-to-rail input/output op amp, DIP-8 (IC2)
1 MCP16251T-I/CH DC-DC boost converter with disconnect, SOT-23-6 (IC3)
1 5mm red LED (LED1)
1 BAT85 30V 200mA schottky diode (D1)

Capacitors

2 10µF 16V X7R multi-layer radial ceramic **[eg, TDK FK26X7R1C106M]**
1 100nF 50V X7R multi-layer radial ceramic
2 22pF 50V C0G/NP0 radial ceramic

Resistors *(all ¼W 5% or better)*

1 2.2MΩ　2 1MΩ　1 820kΩ　3 10kΩ　1 6.8kΩ　1 1kΩ



```
GPS Clock Driver v1.0

Sweep Clock (Y/N) ? Y
Use Daylight Saving (Y/N) ? Y

Start Daylight Saving Month (1-12) ? 10
Start Daylight Saving Day (1=Sun) ? 1
Start Daylight Saving Day in Month (1 to 4=Last) ? 1

End Daylight Saving Month (1-12) ? 4
End Daylight Saving Day (1=Sun) ? 1
End Daylight Saving Day in Month (1 to 4=Last) ? 1

Time Zone (-12.5 to +12.5) ? +10

Configuration Saved
Unplug USB █
```

Screen 1: configuring the clock driver using the USB interface. In this case, sweep clock drive has been selected and daylight saving has been configured to suit NSW/Vic/Tas/ACT. These settings are remembered, so you never have to re-enter the configuration details, even when replacing the battery.

subsequent attempts typically taking under a minute.

Adjusting the second hand

All clock movements allow you to adjust the hour and minute hands, but the second hand will probably not be at the 12 o'clock position and will be stuck somewhere around the dial. To correct this, you can hold down the tactile switch on the PCB while the clock is waiting to start, and the firmware will drive the second hand around the dial. Release it when it reaches the 12 o'clock position.

That way, the clock will start with the second hand indicating the correct second.

A problem with some movements is that when the clock starts running, the movement might start driving the hands a few seconds early or late. While not a big deal, you can adjust for even this slight error while the clock is running. Hold down the tactile switch when the clock is running until the LED illuminates. If you then immediately release the button, the firmware will advance by one second.

On the other hand, if you keep holding down the button until the LED goes off again before releasing it, the firmware will retard the hands by one second.

Remember that a sweep clock will need eight seconds to gain or retard its hands by one second. So, if using a sweep movement, you should wait for a while to check the effect of the last adjustment before making another one.

You can verify your clock is accurate using a time source such as **www.time.gov** which will give you the exact time to the second – even compensating for delays over the Internet. With this as your reference, you can use the tactile switch to bring the second hand to an exact agreement with this source and compensate for any starting error.

You should correct for any startup error immediately after the clock has started running. This is so that you do not inadvertently adjust for an error in the crystal's frequency, which will be automatically corrected by the firmware after the first 12 hours of running, following the second GPS synchronisation.

All clock movements use a type of stepping motor that is locked to the pulse train delivered by the microcontroller. So, once the hands are accurately set, they will never lose or gain a second unless the battery is exhausted or the movement is faulty. Therefore, in the normal scheme of things, you should never have to adjust the clock again after compensating for any initial startup error.

Troubleshooting

To test your clock, insert the cells and observe the LED sequence as described above. Hopefully, it will run through the starting sequence, and the clock will start running. If it does not work as expected, use the LED to help track down the problem.

The LED should flash twice when the cells are inserted (and the USB is not connected). If that does not occur, the fault could lie with the cells, the microcontroller or the LED. Check that the LED is the right way around and that it works before looking for other causes.

If you do not see the double-flash, check the voltage between pins 1 and 14 of the microcontroller. It should be the same as the battery voltage (3.2V with new cells). If that is OK, check the microcontroller. Is its orientation correct? Has it been properly programmed? If you used an IC socket, check that it is properly inserted, with no pins folded underneath.

After the double flash, the firmware will power up the GPS module. Within a few seconds, you should see a brief flash every second on the LED indicating that data is being received from the module. If you do not see this flash, the problem could be with the boost voltage regulator or the GPS module.

Check the voltage between ground and the red wire to the GPS (marked RE on the PCB). It should be about 4V; anything else indicates a problem with the regulator and its associated components.

If the regulator is OK, the fault must be with the GPS module. Check that it is connected correctly and that it uses one of the supported serial communication speeds (4800, 9600 or 19,200 baud).

GPS satellite lock

After a while, the GPS module will get a lock on sufficient satellites to obtain an accurate time. When that happens, the boost regulator will shut down and the LED will change to a long flash every second. Usually this will be within a minute or two, but it could take some time.

There might not be a strong enough signal to get a lock. Take the clock outside and place it so that the antenna is pointing directly at the sky, and leave it that way for at least an hour.

Typically, if the GPS module could gain a lock when you inserted the

Table 1 – DST rules for AU and NZ (not observed in Qld, NT and WA)

	NSW, Vic, Tas and ACT	South Australia	New Zealand
Start month	10	10	9
Start day	1	1	1
Start day in month	1	1	4
End month	4	4	4
End day	1	1	1
End day in month	1	1	1
Time zone offset	+10	+9.5	+12

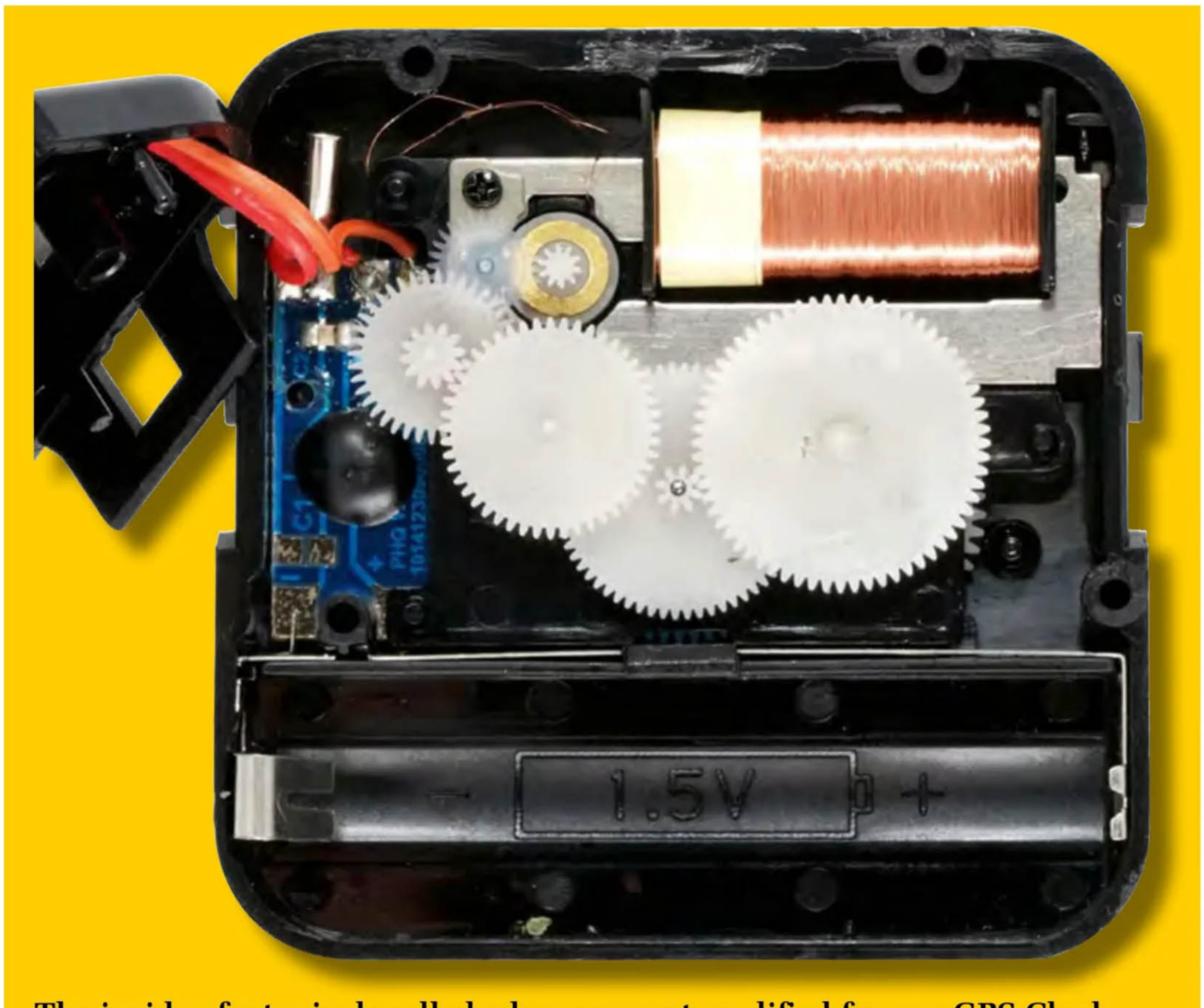
cells, it should be able to get a lock on subsequent synchronisations. However, a marginal signal level or moving the clock might change that.

When the cells are inserted, the firmware will wait forever to get a GPS signal. However, after that first time, the firmware will wait for just 30 minutes to get a signal and then, if unsuccessful, it will give up and retry in 24 hours. To indicate this, the LED will then flash briefly every second until a subsequent attempt is successful and an accurate time is obtained.

If you find that your clock is inaccurate, check the LED. If it is flashing, that indicates there was an insufficient GPS signal to get the accurate time.

If you find that you are getting a short battery life, check the voltage of the exhausted batteries when you replace them. Most movements will keep going down to 1.0V. If it stops at a voltage significantly higher than that (say 1.2V), the movement has too much friction and should be replaced.

We experienced this with a cheap movement that failed after a few years, so it might be prudent to purchase a spare movement (or clock) as a backup in case you need to swap out an old movement. That way, you are guaranteed a replacement that will fit your clock and accept the same hands.


The inside of a typical wall clock movement modified for our GPS Clock Driver. The motor coil is at upper right while the blue control board is on the left, with a blob of black epoxy hiding the control chip. This has been disabled by cutting a PCB trace, and flying leads have been soldered to the motor coil termination points.

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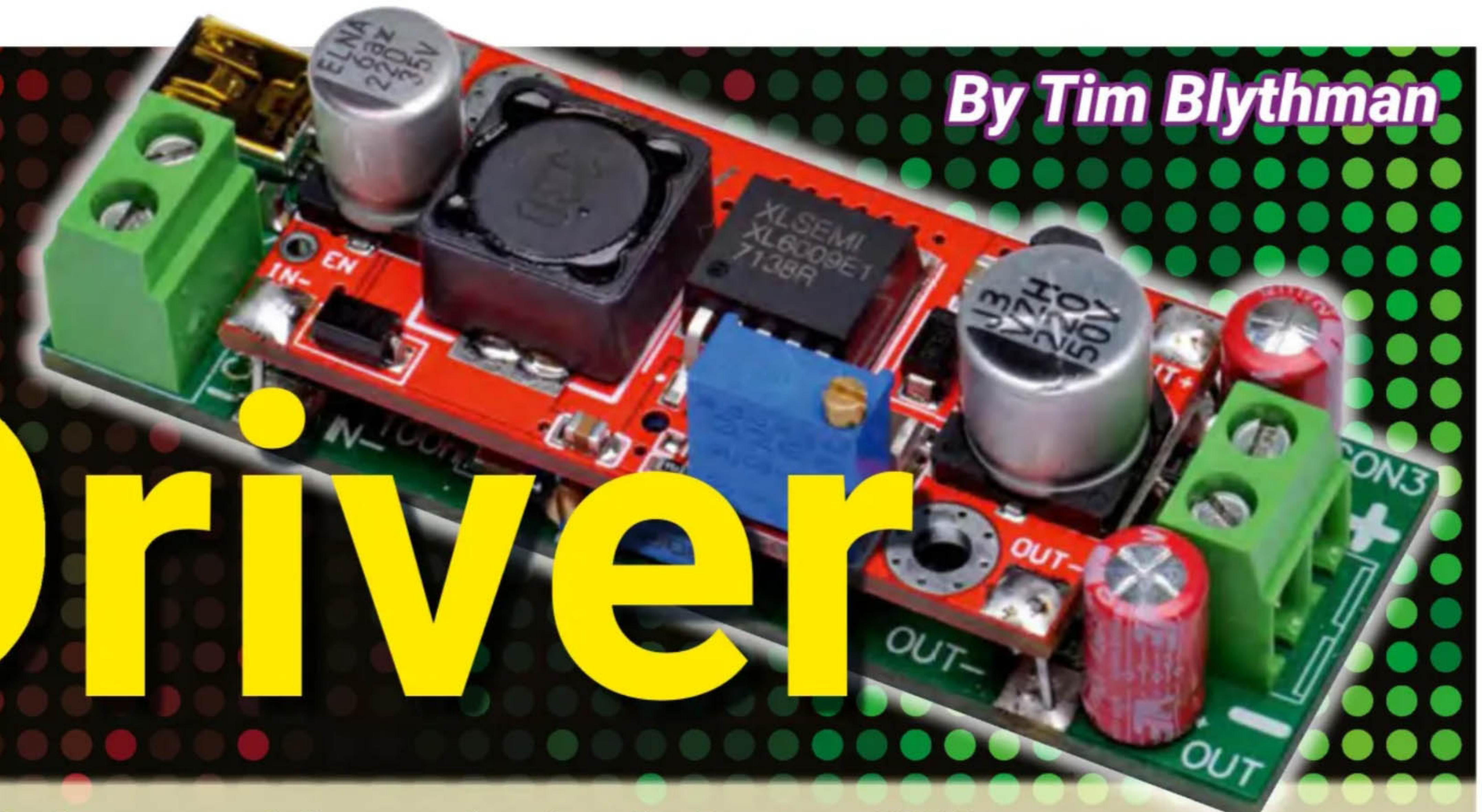
By Tim Blythman

MINI LED Driver



This small, low-cost module can drive relatively large 12V white LEDs from a USB or 5V DC power source. Sometimes you don't need a floodlight; a modest amount of light is enough, and the Mini LED Driver is an economical way to deliver it.

In the June 2023 issue, we featured some 70W LED panels that are incredibly bright when run at their maximum power (around 6A @ 12V). But those panels can still be handy when run at lower currents; they generate quite a bit of light even at 1A/12W, and there are plenty of other white LEDs out there which are designed to run at around 10W. This *Mini LED Driver* is perfect for them.

The main motivation behind it is to safely power 12V LED panels from a 5V DC source. If you're like us, you have many spare USB power supplies or power banks that can be pressed into service to supply 5V.

This *Mini LED Driver* can deliver enough current to drive most white LEDs to provide a good light level. If they're large panels, like the 70W types, then they are so under-driven that their lifespan will be significantly extended due to reduced heat production.

The *Mini LED Driver* is based around the commonly-available, low-cost boost modules using the XL6009 IC, but it adds a few extra features. Those modules don't have inbuilt current limiting except for short-circuit protection; our added circuitry provides an adjustable current limit.

In the June 2023 *High-power Buck-boost LED Driver* article, we explained why it's preferable to run LEDs from a current-limited source. In brief, simply providing a fixed voltage to LEDs will not give consistent light output. Minor voltage variations can cause disproportionately large changes in current, perhaps even enough to damage the LEDs.

The current limiting feature we've added will also protect the input supply, particularly if you're using a small USB power supply to power LEDs that would draw too much current for it to handle at full brightness.

The other feature the *Mini LED Driver* adds is a low input voltage cut-out. This avoids the possibility that the boost module does not perform correctly with a low input voltage. Also, if the power comes from a battery, it will prevent excessive discharging of the battery, which could damage it.

The XL6009 boost module

Numerous DC/DC converter modules are available. They come in two main types – boost and buck – although some modules combine both capabilities.

The buck types reduce the incoming voltage to a lower level. In contrast, buck/boost designs like the Altronics Z6337 (see the photo opposite) contain two controller ICs (and duplicate many other parts) and can either reduce or increase the incoming voltage. These types of module are effectively a boost and buck module combined. But for this project, we're specifically using dedicated boost type modules. These modules have a small PCB that includes a switch-mode boost controller IC, a minimum of passive components, plus a trimpot to set the output voltage. The input and output connections are simply solder pads.

There are many different 'XL6009' module designs floating around, and they do not all perform the same. So, to ensure that you get the correct type, use one with the following specification:

- 49x23mm module that uses the XL6009 (LM2577 equivalent) boost regulator IC.
- Input is 3-32V, output is 5-35V at up to 4A continuous.
- Efficiency up to 96%, switching frequency 400kHz.
- Output voltage is adjusted using a multi-turn trimpot.
- The input and output DC connections are made via pads in the corner of the PCB.
- The version we used has a red PCB, a single inductor and SMD electrolytic capacitors in metal cans. Note that there are at least two other red PCB versions, both with two inductors, plus others with blue PCBs. We haven't tested them all so it's best to stick to the version shown above.
- We recommend eBay items 253022096489 or 253958534625; or from AliExpress you can use: **https://bit.ly/pe-sep23-alx1** or **https://bit.ly/pe-sep23-alx2** (option 'XL6009 Red').

We have used modules based on the MT3608 IC for some previous projects. In those cases, the module is soldered directly to another PCB and treated as

Features and Specifications

- **Can drive 12V LEDs or LED panels from a 5V DC supply (eg, USB)**
- **Adjustable output current and voltage, up to 1A/20V**
- **Small and low in cost**
- **Input up to 4A/20V, subject to boost module capacity**

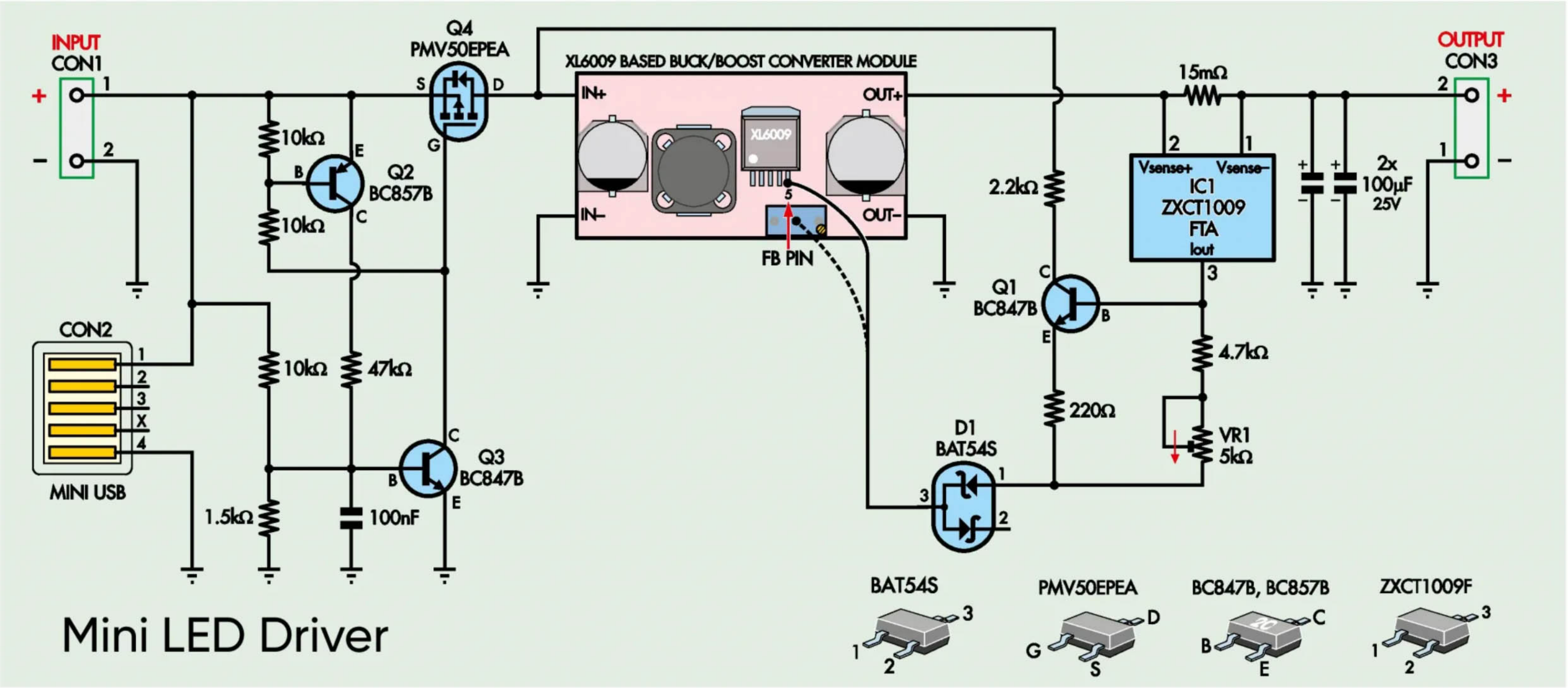


Fig.1: the Mini LED Driver circuit has two main sections. The first section provides the low-voltage cut-out function, using transistors Q2-Q4 and associated passives. The second samples the current between the boost module and the output at CON3 and injects a signal back into the boost module after diode D1 to limit the output current to a more-or-less fixed level.

though it were just another component, much like the *Mini LED Driver*.

The *Arduino-based Programmer for DCC Decoders* (October 2019) similarly used such a module to derive 12V power from a 5V USB supply. In that case, 12V was needed to correctly power and program the DCC decoders.

For the *Mini LED Driver*, we have chosen a different boost module. The XL6009 IC makes it more capable than the MT3608-based module, giving headroom to operate the module comfortably within its limits.

Implementing the current limiting feature with the XL6009-based module is also slightly easier. It's somewhat larger, but the complete *Mini LED Driver* still measures just 72mm by 24mm.

One caveat with these modules is that reader Jonathan Woithe wrote in to tell us that these modules do not always regulate their output voltage correctly under some input voltage conditions. This means that the module can produce up to 50V, even when set lower, which is clearly not desirable!

This problem only occurs when the incoming supply voltage is below the minimum specified voltage for the XL6009 IC. So, for example, if the module is powered by a battery that runs flat, it may be subject to these output spikes. We avoid this problem by shutting down the XL6009 module when the incoming voltage is low while also providing battery over-discharge protection.

The *Mini LED Driver* is presented as a bare PCB and is intended to be used as an enhanced module as part of a larger assembly that might include a power supply and an LED panel or another device that uses power from the *Mini LED Driver*.

So the *Mini LED Driver* provides three main functions over a simple boost module: it's easier to connect to, has current limiting and a low-voltage cut-out.

We haven't tested the *Mini LED Driver* in other applications. Still, it could be handy to help charge a 12V battery with the appropriate settings and a diode on the output, or anywhere a 12V DC source is needed at modest currents (up to about 1A).

Circuit details

Fig.1 shows the circuit diagram of the *Mini LED Driver*. The input supply is wired to either CON1 or CON2, while the LEDs (or another load) connect to CON3.

CON1 is a pair of screw terminals to which you can connect bare wires. This type of connector will handle up to 5A with ease. Mini-USB connector CON2 makes it convenient to power it from a USB power supply, but most USB connectors will not handle more than about 2A, so the screw terminals are better for higher input currents.

CON3 is another screw terminal block from which power can be drawn. If the low-voltage cut-out and current limiting are not operating, the *Mini LED Driver* behaves just like a boost module.

Circuit ground from inputs CON1 and CON2 is connected straight through to output CON3 and to the boost module's ground terminals, IN– and OUT–.

The low-voltage cut-out connects between the CON1 and CON2 inputs and the boost module, switching power to the module's IN+ terminal. The low voltage cut-out works as follows.

A divider formed by 10kΩ and 1.5kΩ resistors connects across the incoming supply. The junction of these two resistors connects to the base of NPN transistor Q3. When the voltage at this junction is above about 0.6V, Q3 is switched on, and it pulls the gate of P-channel MOSFET Q4 down, powering the boost module.

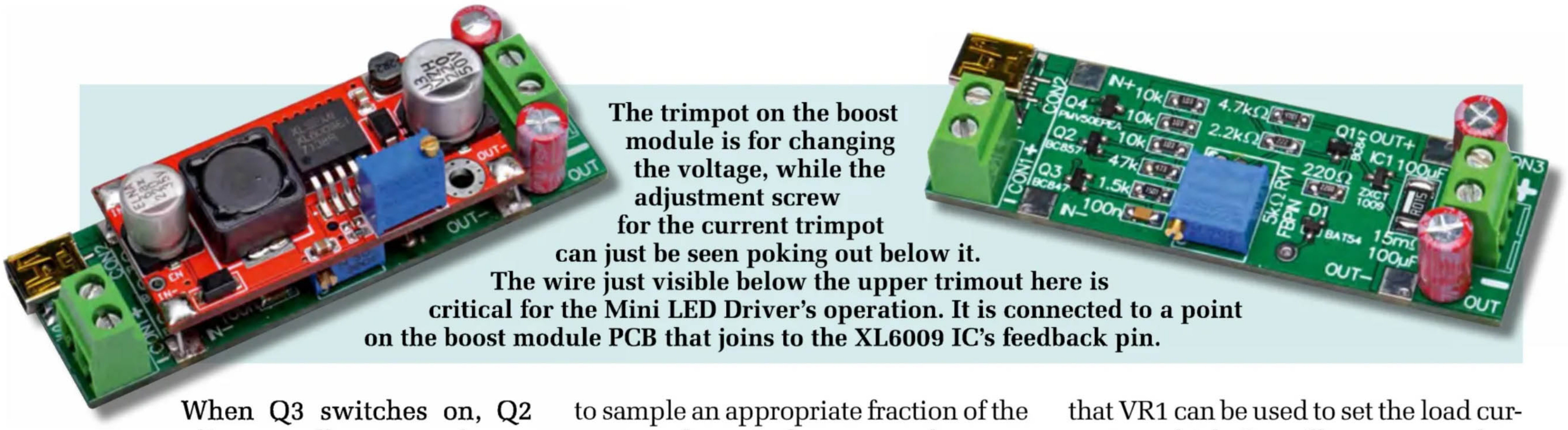
The 10kΩ/1.5kΩ divider means that an input voltage of about 4.6V is needed to switch on Q3, along with Q2 and Q4.

At the same time, Q3 sinks current from the base of PNP transistor Q2 via a pair of series-connected 10kΩ resistors, which serve both to limit the current sunk from Q2's base and ensure it is held off when Q3 is not sinking current. These two resistors also hold Q4's gate high when Q3 is off, so it is also switched off when appropriate.

There are two resistors because Q4's gate needs to be pulled more than 1V below the supply voltage to switch it on, while Q2's base-emitter junction limits its base voltage to around 0.6V below the incoming supply.

The 47kΩ resistor between Q2's collector and Q3's base provides some hysteresis for this voltage comparator.

This Altronics Z6337 buck-boost module uses two controller ICs and two inductors to provide separate buck and boost capabilities. The Mini LED Driver is intended to be used with a boost-only module.



The trimpot on the boost module is for changing the voltage, while the adjustment screw for the current trimpot can just be seen poking out below it. The wire just visible below the upper trimout here is critical for the Mini LED Driver's operation. It is connected to a point on the boost module PCB that joins to the XL6009 IC's feedback pin.

When Q3 switches on, Q2 supplies a small amount of extra biasing current into the junction of the 10kΩ/1.5kΩ voltage divider. This means that the input voltage needs to drop to around 3.9V before Q2, Q3 and Q4 switch off.

This reduces the chance of the low-voltage cut-out oscillating when the input voltage is close to the cut-out point. The 100nF capacitor in parallel with the 1.5kΩ resistor also helps by further slowing down its response.

The default resistors have been chosen to give correct operation with a nominally 5V USB supply and protect against such things as the USB supply's voltage dropping.

Although not explicitly designed for it, the *Mini LED Driver* can operate from higher voltages. We will mention some of the provisos and limitations later.

By the way, the 20V maximum limit of this design is due to the maximum gate-source voltage rating of MOSFET Q4, while Q4 also limits the current fed to the boost module to 4A as its drain current limit is 4.2A. Still, the XL6009 module tops out at around 4A anyway, so using a beefier MOSFET wouldn't gain us much.

We have not added any input current limiting as most USB supplies will lose control before delivering 4A.

Current limiting

The XL6009 IC on the boost module controls the output voltage by comparing an internal voltage reference to a fraction of the output voltage, and adjusting its operation to try to keep them the same. The trimpot on the boost module is part of a resistive voltage divider used to sample an appropriate fraction of the output voltage. So the output voltage can be set by adjusting the trimpot.

We provide current limiting by injecting current into this voltage divider, making it appear to the switch-mode chip that the output voltage is higher than it actually is, causing it to reduce its output.

A 15mΩ shunt resistor is connected between the boost module's output (OUT+) and output connector CON3. The voltage across this resistor is proportional to the current drawn by the load at CON3. The ZXCT1009 shunt monitor IC (IC1) amplifies this voltage difference and converts it to a current that flows from its pin 3 output. This current is 10mA for each 1V across the shunt.

Note that the 15mΩ shunt resistor reduces the voltage applied to the load, but as its value is low, the difference is only a few millivolts (15mV at 1A), so it is not important.

Since a 1A load current will induce 15mV across the 15mΩ shunt resistor, that will result in 150μA flowing from pin 3 of IC1 (10mA × 15mV ÷ 1V). The upshot is that IC1 produces a current that is 1/6667 (or, if you prefer, 3/20000) that of the output current.

This current is fed to the FB (feedback) pin on the attached boost module through the 4.7kΩ resistor, trimpot VR1 wired as a variable resistor and schottky diode D1. This current will tend to reduce the output voltage in proportion to the current, but this is not the main factor in the current-limiting circuitry. There is also NPN transistor Q1 to consider.

Q1's base and emitter (with a 220Ω emitter degeneration resistor to moderate its gain) are connected across the 4.7kΩ resistor and VR1. If more than 0.6V appears across those two components, Q1 will start to conduct.

This action forms the bulk of the current-limiting feature, with the extra current being sourced into the FB pin through Q1's collector and emitter. The 2.2kΩ collector resistor limits the maximum current that can be injected, helping to keep this arrangement stable.

The voltage between the base and emitter of Q1 depends on both the load current and the setting of potentiometer VR1. So, based on Ohm's law, that means that VR1 can be used to set the load current at which Q1 will start to conduct and therefore the maximum current that the whole device can supply.

Note that if you use a supply voltage different to 5V, the current limit will change due to Q1's collector resistor connecting to the incoming supply. But most sources of 5V DC are regulated, so this generally won't matter. It is something to keep in mind if you're going to power this circuit directly from a battery pack.

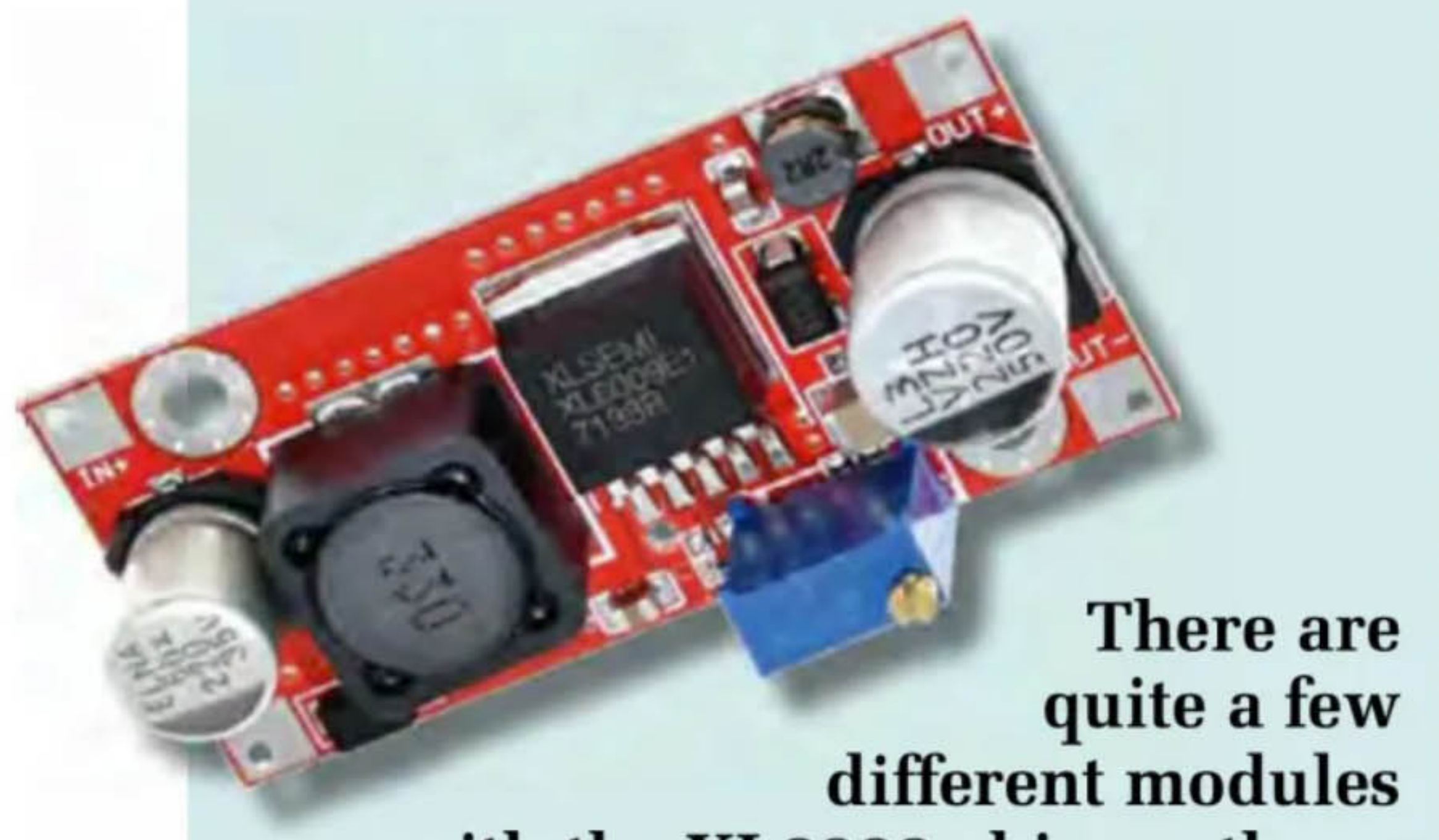
Finally, there are two capacitors connected across the output. We have used two smaller parts here as they fit the outline of the *Mini LED Driver* better. They smooth out the voltage across the shunt resistor, which would otherwise be quite peaky due to the upstream capacitors on the boost module.

Due to this, the *Mini LED Driver* is not well suited as a current-regulated source for dynamic loads, as these capacitors can only allow a slow response. If the load resistance suddenly changed, then these capacitors would need to charge or discharge before the system could settle at a new steady state. During this time, the current through the shunt would not represent what is happening downstream of CON3.

Fortunately, LEDs present a slowly changing load. The *Mini LED Driver* just needs to cope with changes that occur as the LED forward voltage changes with slowly changing variables such as temperature.

Keep in mind that this current-limiting scheme is not effective as short-circuit protection, because the boost module cannot reduce its output voltage below its input voltage (except for the small drop due to its onboard diode).

Basically, the Mini LED Driver cannot limit its output voltage to anything much below its input voltage and certainly not down to levels near zero.



There are quite a few different modules with the XL6009 chip on them. This is the one we found worked best, and it's inexpensive.

Current adjustment

VR1 is wired such that the fully clockwise position corresponds to 0Ω between its two connected terminals. So the clockwise position sets a 4.7kΩ resistance between IC1's I_{OUT} and the diode, while the fully anti-clockwise position thus sets a 9.7kΩ resistance.

Assuming a threshold of around

0.6V for a silicon base-emitter junction, Q1 will start to conduct at 127µA from IC1 when VR1 is set fully clockwise, and 62µA from IC1 when fully anti-clockwise.

This means that the usable output current setting range is nominally from 0.85A down to 0.41A (recalling the factor of 6667 explained previously), although these are not hard limits.

During one of our tests, we started by setting the *Mini LED Driver* voltage to 12V with no load and with VR1 set to its minimum. We then connected one of the large 70W LED panels and measured a panel current of 0.48A at 11.1V.

Setting the current limiting to maximum gave 0.84A at 11.3V but the current could be increased to 1A by increasing the voltage setpoint (at no load) to around 12.6V. We measured close to 3A at the 5V input, so we don't expect many USB supplies will work at these levels anyway.

The fact is, the current limiting comes on gradually, which is necessary to keep the *Mini LED Driver* stable. It also means that the LED operating point can be tweaked by careful adjustment of both the current and voltage settings.

Fig.2 shows the effects of changing loads on the *Mini LED Driver*. We made these plots with the no-load voltage set to 12V and the current-limiting trimpot set to its lowest and highest positions, plus a third point near the middle.

There is a limit to how low a voltage can be achieved by the current limiting circuitry; around 8.3V in this case. That is due to the 2.2kΩ resistor limiting the current injected into the voltage divider.

Other boost modules that use different divider resistors for their voltage setting will behave differently as the injected current will change the setpoint by a different amount. This is one of the reasons we're recommending a specific module, as shown in the photos opposite. This is the one that worked the best in our testing.

If you must try a different boost module, we recommend thoroughly testing the combination before putting it to use. We used the *Arduino Programmable Load* from the June 2022 issue for much of our testing, including plotting Fig.2.

Efficiency

We also measured the module's efficiency and found that it did not reach the 96% figure claimed by the suppliers of many of these boost modules. They usually specify the efficiency for boosting 12V to 20V; boosting 5V to 12V is both a higher ratio and starting from a lower voltage, so efficiency will not be at its peak.

With a regulated 5V DC input and 12V at the output, a helpful rule of thumb is to multiply the output current by three to work out the theoretical input current. This corresponds to an approximate efficiency of 80%.

Options

You might decide to leave off CON1 or CON2 if you know that you will definitely only use one of them, but we'll explain the construction procedure as if fitting both.

Keep in mind that the *Mini LED Driver* will draw a considerable current with a 5V supply. Any significant sag in its input voltage could result in the low-voltage cut-out operating.

A USB connector will have a noticeably higher resistance than the screw terminals. So, we recommend fitting both in case this resistance turns out to be too high, and you need to use the screw terminal instead of the USB connector.

Construction

This board is not difficult to assemble, but it almost exclusively uses surface-mounting parts. So ensure you have the necessary tools and supplies, including solder, flux paste, solder wicking braid, a fine-tipped iron (or at least not a huge one), tweezers, decent lighting and a magnifier.

For more tips and tricks regarding SMD soldering, see our feature on the topic in the December 2022 issue.

The PCB is well-marked, but you can also refer to the overlay diagram (Fig.3) to see which parts go where. The PCB is coded 16106221, measures 72mm x 24mm and is available from the *PE PCB Service* .

Start with CON2, the mini-USB connector. Apply flux to the pads and rest the connector in place. It has locating lugs, so it should lock into the correct position.

Clean the soldering iron tip and apply a small amount of fresh solder. Touch the iron to the two extended end pads in the row of five – only these two are needed to supply power. If you bridge them to any other pins, use the solder wick to remove any excess before proceeding.

Then apply a generous amount of solder to secure the four corner leads on the shell, which will ensure that the connector is mechanically secure.

Work through the transistors, diode and IC next. They are all in identical-looking SOT-23 packages, but there are five different types, so take care that they are not mixed up. The PCB is marked with the part numbers as well as the designators.

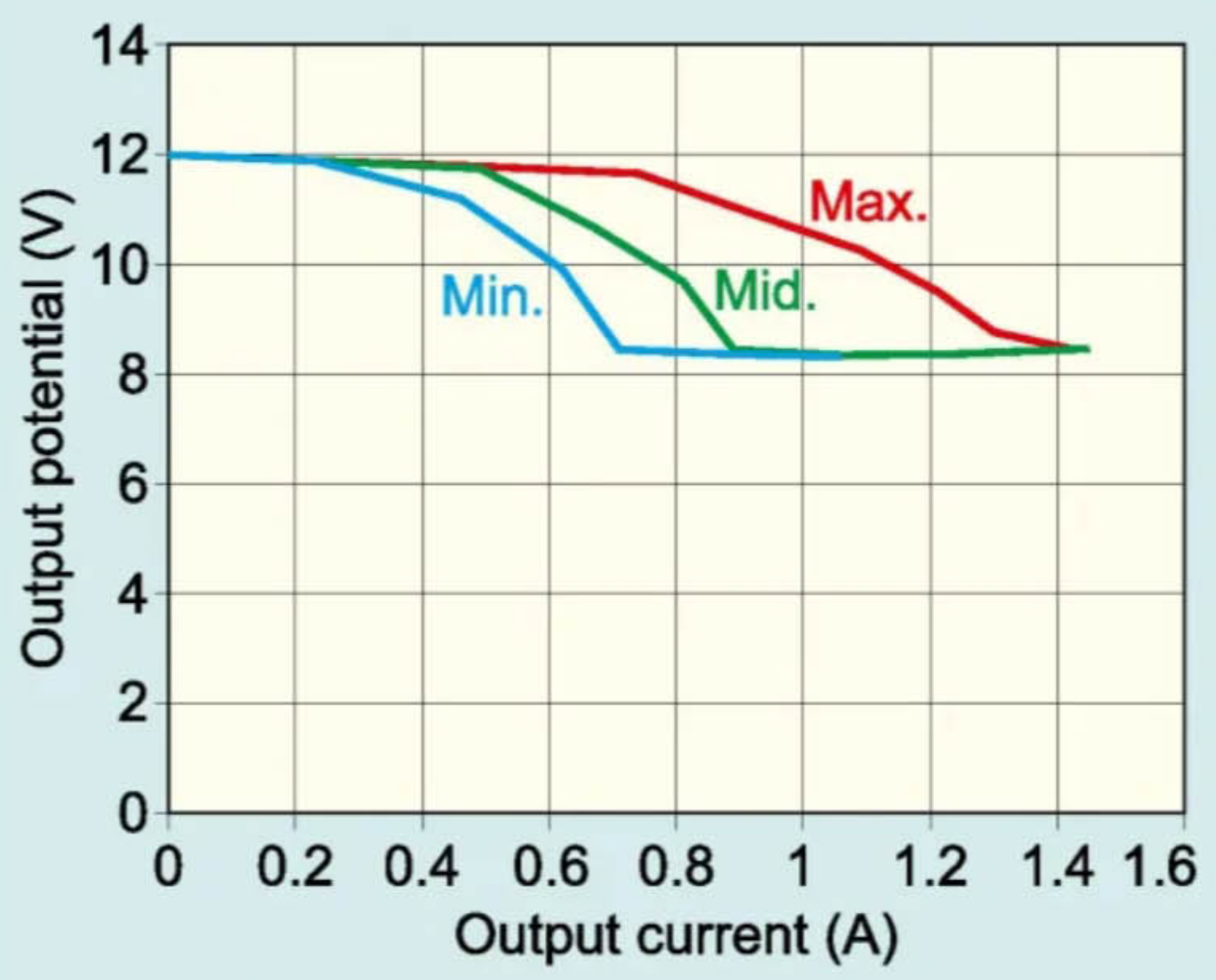


Fig.2: these curves show the behaviour of the Mini LED Driver when set to a nominal 12V and three different current limit settings. The curves correspond to VR1 at minimum (cyan/blue), maximum (red) and roughly halfway between the two extremes (green).

Check the types against the overlay, working with one type at a time. The SOT-23 parts are small, but the leads are pretty spread out, so they are quite easy to work with.

Apply flux to the pads for these parts, then use tweezers to roughly place each part in turn. Tack one lead and check that the remaining leads are all within their pads. If not, adjust as necessary using the iron and tweezers. Then solder the remaining leads.

Do the same with the eight small (3.2 × 1.6mm) resistors, checking their values against the silkscreen as you go. Much the same technique is used for these parts as for the semiconductors.

Fit the larger (6.3 × 3.2mm) current shunt resistor next. It is harder to mix up with the other parts because of its unique size for this project. The solitary SMD capacitor goes next to the 1.5kΩ resistor and can be soldered similarly.

That completes the fitment of the surface mounting parts. Next, clean the PCB of any flux residue before proceeding further – and do allow the board to dry thoroughly.

You can test the low-voltage cut-out feature if you can connect a variable power supply to the CON1 or CON2 inputs. It's best to do so now, before connecting the boost module, as it's easier to fix any problems you find. Do not exceed 20V, and mind the polarity of the connections to CON1.

Ramp the input voltage up and down. Check that the voltage between the IN+ and IN– points is present when CON1 or CON2 is above the upper threshold (around 4.6V). When the input is below the lower threshold (near 3.7V), it should drop out.

Completion

The remaining parts to mount are CON1, CON3, trimpot VR1, the two electrolytic capacitors and finally,

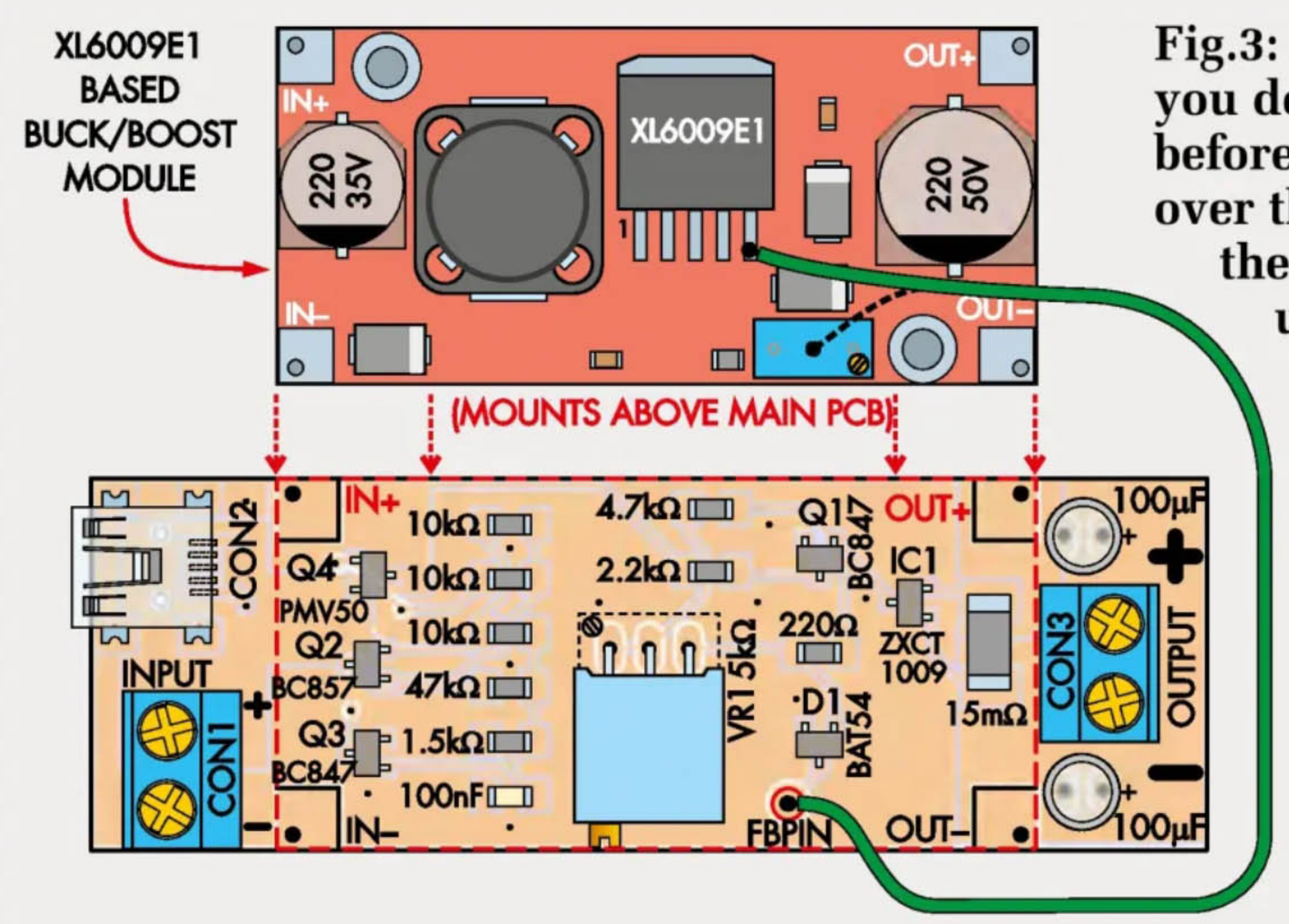
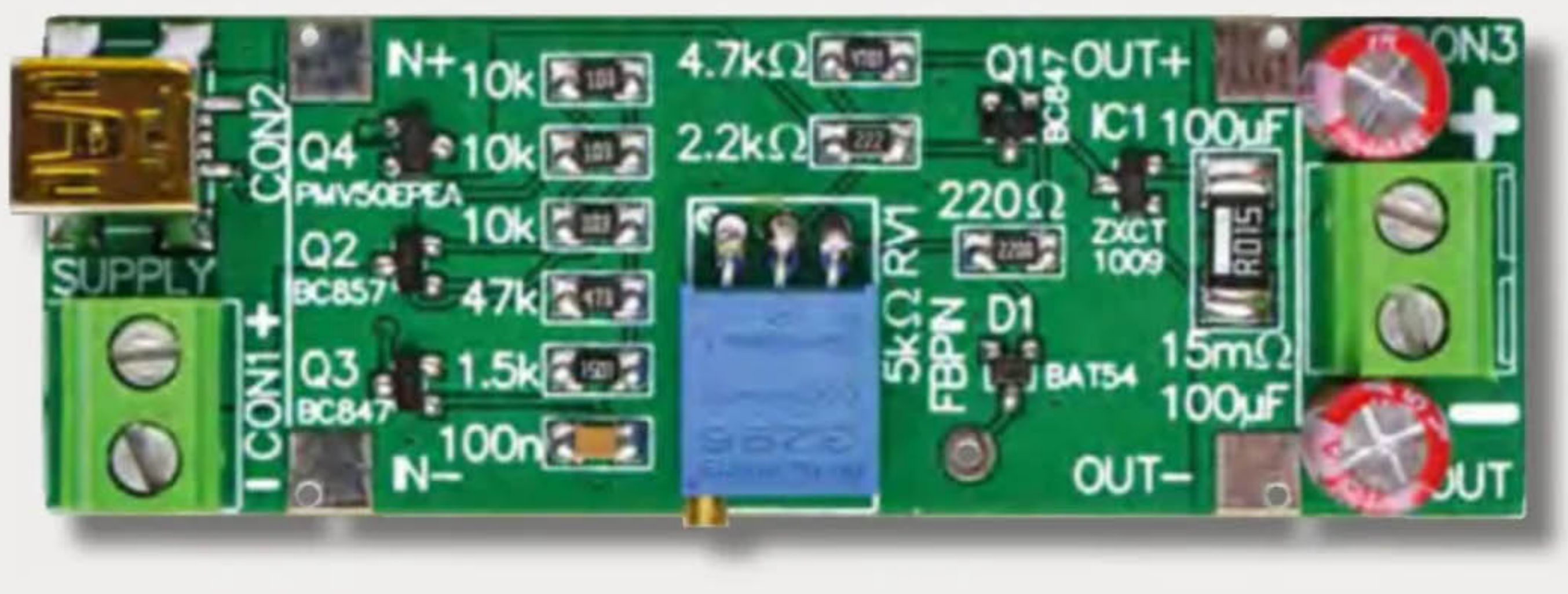


Fig.3: the trickiest part of assembling the Mini LED Driver is ensuring you don't mix up the various SOT-23 parts. Check the PCB markings before soldering these components in place. The boost module sits over the top of this PCB, as you can see from our other photos. While the feedback connects electrically to pin 5 of the XL6009 IC, it's usually easier to solder to a trimpot lead after checking for a low resistance between it and the IC feedback pin.



the boost module. Solder CON1 and CON3 first. They should sit far enough apart to allow the boost module to sit between the connectors on the ends.

Fit VR1 next. While you could solder it in the standard vertical position, the boost module will sit over the *Mini LED Driver* PCB, blocking adjustment. So instead, install it on its side, as shown in our photos. Ensure that the adjustment screw is positioned correctly. You should also adjust the trimpot to its minimum (fully anti-clockwise) in preparation for testing.

The two electrolytic capacitors sit near CON3. The longer positive leads go into the pads marked with small + symbols. Push them down firmly against the PCB before soldering and trimming the leads.

A warning before fitting the boost module; we have seen some boost modules that (confusingly) increase their voltage when the trimpot is adjusted counter-clockwise.

If you are using a different module from the type we supply, check its voltage by powering it up and measuring its output with a multimeter before soldering it to the *Mini LED Driver* board. Otherwise, you could cook those two capacitors the first time you power it up.

Having checked that, solder the short length of wire to the feedback pin at the reverse of the voltage adjust trimpot on the underside of the boost module. It is intended to be connected to the middle pin, to align with the other PCB, but you might see that two of the boost module's trimpot's pins are connected together anyway.

You can see where this connects in our photos. On the XL6009 modules that we are using, this should line up directly with the FBPIN pad on the *Mini LED Driver* PCB, but it might be in a different location if you are using a different module.

Since it lines up directly, a component lead off-cut might be adequate, but if you can't run the wire directly, use a short length of fine insulated wire instead (eg, Kynar or wire wrap wire).

Now solder component lead offcuts or short lengths of stiff wire to the four corners of the boost module at the IN+, IN–, OUT+ and OUT– pads. These should all face down in the same fashion as the wire going to FBPIN. We found a pair of tweezers or pliers handy to grip the wire while soldering it (to avoid burned fingers).

Now you can join the two boards together with the boost module above the *Mini LED Driver* PCB, ensuring that the pad labels match. Allow some clearance between the two PCBs if possible, and tack one lead in place.

Adjust the boards to ensure that nothing is making contact where it shouldn't and check that they are square and parallel, then solder the four corner pads followed by the wire for FBPIN. Trim any wires that are longer than necessary.

Testing

During testing, remember that the *Mini LED Driver* is not short-circuit proof. So take care with the attached loads to ensure that there is no chance of a short circuit or very low resistance that might overload MOSFET Q4.

As we mentioned earlier, the *Arduino Programmable Load* works well for testing, but you could use a fixed resistor (eg, 22Ω 10W or two 10Ω 5W resistors in series) or a high-power white LED. The following assumes a 5V supply and might not work if you have a much higher supply.

Apply power without a load and adjust the CON2 output to 12V using the XL6009 module trimpot. If you can't smoothly adjust the voltage at the output, check the *Mini LED Driver* assembly before proceeding further. Remember to not set the output above 20V!

With VR1 on the Driver set to its minimum position, a 20Ω or lower

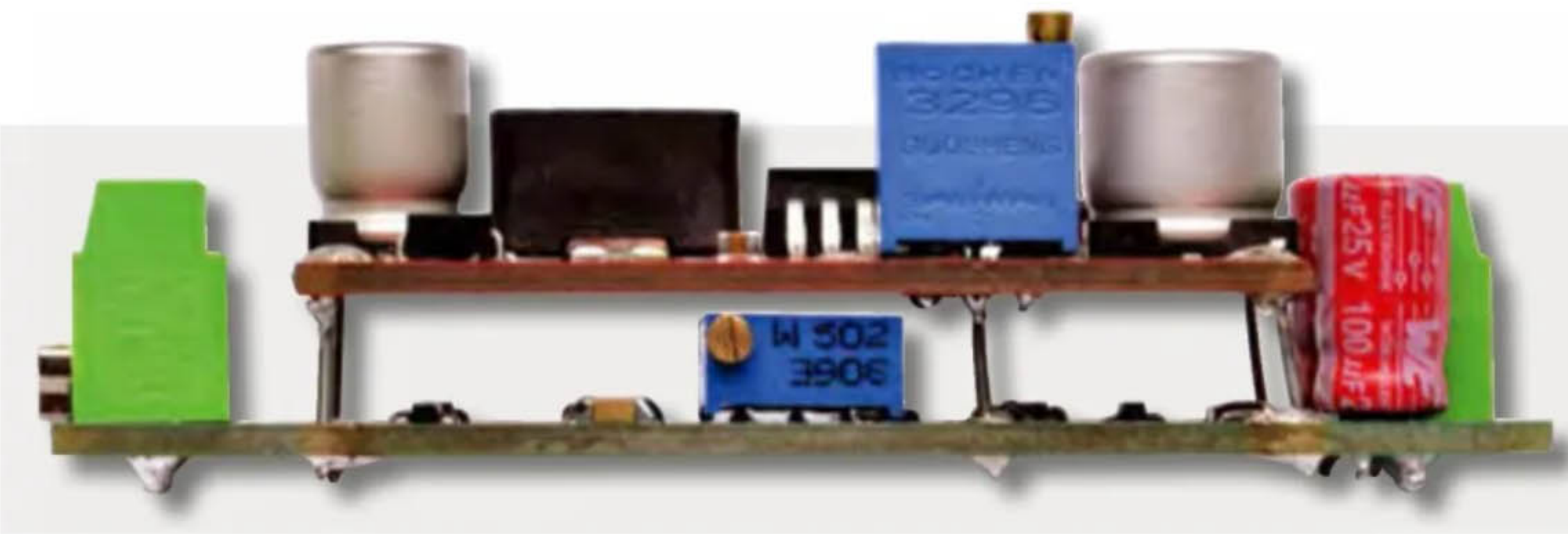
Parts List – Mini LED Driver

1 double-sided PCB measuring 72mm x 24mm, coded 16106221
1 DC-DC boost module based on XL6009 controller with red PCB (MOD1, see text) **[See Silicon Chip part SC6546 for part specification: www.siliconchip.com.au/Shop/]**
1 2-way, 5.08mm screw terminal block (CON1) ***AND/OR***
1 mini-USB socket (CON2)
1 2-way, 5.08mm screw terminal block (CON3)
5 20mm lengths of 1mm diameter solid core wire or component lead off-cuts (see text)

Semiconductors
1 ZXCT1009 high-side current shunt monitor, SOT-23 (IC1)
1 BAT54 (or BAT54C or BAT54S) schottky diode, SOT-23 (D1)
2 BC847B NPN bipolar transistors, SOT-23 (Q1, Q3)
1 BC857B PNP bipolar transistor, SOT-23 (Q2)
1 PMV50EPEA or AO3407 P-channel MOSFET, SOT-23 (Q4)

Capacitors
2 100µF 25V electrolytic
1 100nF 50V X7R M3216/1206 SMD ceramic

Resistors *(all 1206/M3216 ⅛W unless specified otherwise)*
1 47kΩ 3 10kΩ 1 4.7kΩ 1 2.2kΩ 1 1.5kΩ
1 220Ω 1 5kΩ top adjust multi-turn trimpot (VR1)
1 15mΩ 2512/M6432 3W current shunt resistor



You can clearly see the wire from the FBPIN pad to the trimpot above.

resistance load should draw near 0.6A and cause the output to enter current limiting. Referring to Fig.2, check that your unit responds similarly to our prototype.

If the output voltage or current seems to be dropping more than this, check that your USB supply is operating within its limits. It might have its own internal current limiting. If the voltage at CON1 is not being maintained near 5V, that is a sign that the supply you are using is not handling the load.

It is a good idea to check the voltage going to the boost module at the IN+ and IN– pads. If this is much less than the voltage at CON1, the low-voltage cut-out is operating. That may be due to voltage drops in the cable or the USB supply sagging under load.

Adjust VR1 and check that the current limit changes. You might need to increase the load (decrease the resistance) by adding extra parallel resistors. Set the current to your desired value and connect your desired load. Then, confirm that this configuration works as expected.

Using other boost modules

We don't recommend this unless you are experienced. Finding the feedback (FB) pin can be tricky if your boost module is not labelled. A good place to start is the centre pin of the adjustment trimpot, although we have seen some modules that do not follow that trend.

The FB pin is brought out on the XL6009 IC, and most boost controllers should have an external feedback pin, so it makes sense to start looking there. On the XL6009, it is the rightmost of the small pins (pin 5). On the modules we have tried, it is the smaller pin closest to the voltage adjustment trimpot.

You could solder a wire directly to this pin, although it won't be as neat as connecting to the adjustment trimpot terminal. Instead, you can use a multimeter set on continuity mode to find another more accessible (eg, through-hole) solder joint with a near-zero resistance to the feedback pin. If in doubt, look for a data sheet for the switchmode controller chip on your module.

Using it

We tried the *Mini LED Driver* with one of the large 70W LED panels we used in June with the *Buck-Boost LED Driver*. We connected the LED panel after setting the output to 12V with no load and winding the current limiting to its minimum.

It drove the panel at 480mA, with the output voltage being 11.1V. Slowly increasing the current limit increased the panel current and brightness. To confirm that the current is being adequately regulated, disconnect the LED panel and check that the output voltage rises by at least half a volt; this means that there is headroom for the *Mini LED Driver* to regulate its current.

We found that the panel would dim and sometimes flicker after the current was set past a certain point, meaning that the USB power supply had reached its limit.

Another symptom of overloading is a high-pitched sound from the boost module when under load. If this occurs, then wind the current limit down to prevent damage to the USB supply.

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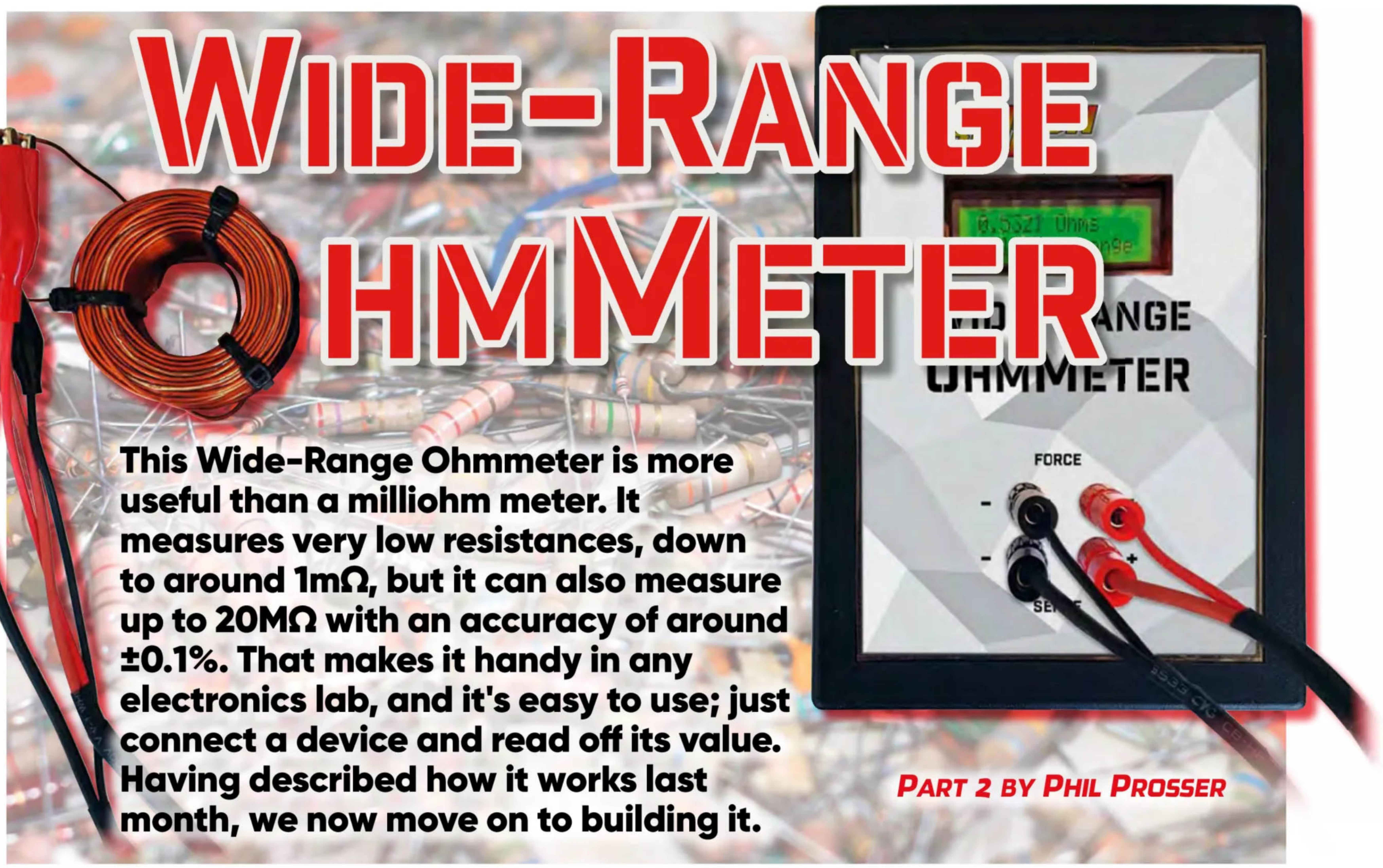
WIDE-RANGE OHMMETER



This Wide-Range Ohmmeter is more useful than a milliohm meter. It measures very low resistances, down to around 1mΩ, but it can also measure up to 20MΩ with an accuracy of around ±0.1%. That makes it handy in any electronics lab, and it's easy to use; just connect a device and read off its value. Having described how it works last month, we now move on to building it.

PART 2 BY PHIL PROSSER

Construction is relatively straightforward as most parts mount on a single modestly-sized PCB. The four binding posts/banana terminals mount on the case's front panel and are wired up via two figure-eight leads and two-way locking header plugs. The six-AA battery holder is stuck to the base of the case and hard-wired to the on/off switch, with power going to the PCB via another header plug.

The rest of the parts are on the PCB, which mounts behind the front panel of the case. Several of these parts are only available in SMD packages, so some surface-mount soldering is inevitably involved. Still, we have tried to make it relatively easy.

You need the right tools, including a temperature-controlled iron, a syringe of flux paste, solder wick, a good light and a magnifier. It's also essential to exercise patience; it's easier to make mistakes if you rush into soldering these devices. A little practice soldering fine-pitched SMDs also wouldn't go astray (using our *SMD Trainer* from the December 2022 issue).

Don't feel daunted; we believe most constructors with modest soldering experience can build the *Wide-Range Ohmmeter* without too much difficulty. So let's start the assembly process.

Construction

The *Wide-Range Ohmmeter* is built on a double-sided PCB coded 04109221, measuring 90.5 × 117.5mm and available from the *PE PCB Service*. Fig.6 is the overlay diagram, which shows which parts go where. Start by checking the PCB, checking that you have all the required parts and tools.

Commence by mounting the SMDs. The usual advice for soldering these goes: use plenty of flux, take your time, use a loupe or good handheld magnifier to check, then double-check for bridges between tracks and when you find them, use solder wick to remove them. Oh, and leave the quadruple espresso coffee until after you are finished.

One of the most important things to do, and we can't stress this enough, is to check that you have the right part in each location and that *it is orientated correctly* before you solder more than one or two pins. While it is possible to remove an SMD IC that has been fully soldered – without damaging it or the board, then cleaning up the board to re-solder it – it is a lot of work!

Some MAX11XXX ADCs have a chamfer along the pin 1 side and no dot to indicate pin 1. So if you can't find the dot, look at the IC edge-on under magnification; hopefully, you can spot the chamfered edge. Pin 1 is on that side.

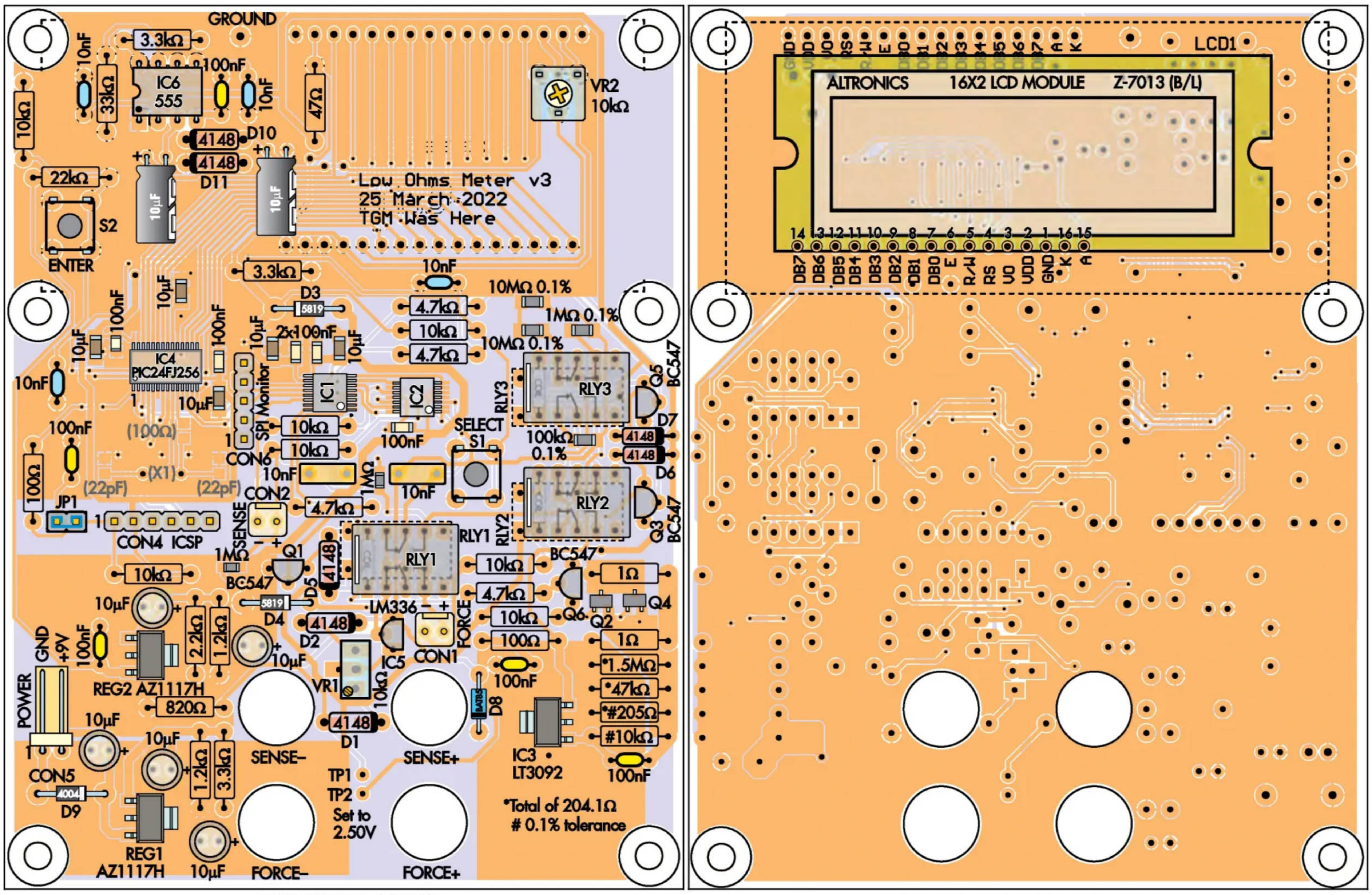
It's also an excellent idea to use your magnifier to check carefully that all of an IC's pins are correctly located over its pads after soldering one pin in each corner, before soldering the rest. It's easy for an SMD IC to shift slightly if you just tack one pin, and very hard to fix the alignment after soldering more than a few.

Besides most ICs and regulators on the board being SMDs, there are also a handful of surface-mounted bypass capacitors and resistors, but they are much larger and easier to solder. It's generally best to start with the fine-pitch ICs; that way, you have the best view and access to their leads.

So, fit IC1, IC2 and IC4 first (remember what we said about checking their pin 1 markings first!), then MOSFETs Q2 and Q4, followed by IC3, REG2 and REG3 (don't get the different types mixed up). Follow with the five smaller 100nF SMD ceramics, the remaining 10µF SMD ceramics and then all the SMD resistors.

Clean off any gross flux residue (using a special-purpose flux cleaner or pure alcohol), then, under good light, check every pin on the SMDs for bridges.

Some phone cameras can zoom in for a really close-up photo; if yours


GROUND
3.3kΩ
10nF
100nF
IC6
555
10nF
47Ω
VR2
10kΩ
10kΩ
33kΩ
4148
D10
4148
D11
22kΩ
10µF
10µF
S2
ENTER
Low Ohms Meter v3
25 March 2022
TGM Was Here
3.3kΩ
10nF
D3
5819
10MΩ 0.1%
4.7kΩ
1MΩ 0.1%
10kΩ
10MΩ 0.1%
4.7kΩ
2x100nF
IC4
PIC24FJ256
IC1
IC2
RLY3
Q5
BC547
10nF
100nF
(100Ω)
SPI Monitor
10kΩ
10kΩ
SELECT
S1
100kΩ
0.1%
D7
4148
4148
D6
(22pF)
(X1)
(22pF)
CON6
10nF
10nF
1MΩ
RLY2
Q3
BC547
100Ω
JP1
CON4 ICSP
4.7kΩ
SENSE
CON2
RLY1
10kΩ
1MΩ
Q1
BC547
4148
D5
RLY1
10kΩ
BC547
1Ω
Q4
10µF
D4
5819
4.7kΩ
LM336
10kΩ
Q6
Q2
GND
+9V
100nF
2.2kΩ
1.2kΩ
4148
D2
FORCE
CON1
100Ω
1Ω
POWER
REG2 AZ1117H
820Ω
VR1
10kΩ
IC5
100nF
1.5MΩ
47kΩ
10µF
10µF
SENSE–
4148
D1
SENSE+
D8
#205Ω
#10kΩ
CON5
1.2kΩ
3.3kΩ
TP1
TP2
IC3
LT3092
100nF
D9
4004
Set to 2.50V
*Total of 204.1Ω
# 0.1% tolerance
REG1
AZ1117H
10µF
FORCE–
FORCE+
LCD1
ALTRONICS
16X2 LCD MODULE
Z-7013 (B/L)
DB7
DB6
DB5
DB4
DB3
DB2
DB1
DB0
E
R/W
RS
V0
VDD
GND
K
A
14
13
12
11
10
9
8
7
6
5
4
3
2
1
16
15

TOP (REAR) OF PCB

UNDERSIDE (FRONT) OF PCB

Fig.6: most of the components are mounted on the top side of the PCB. The only part on the underside is the 16×2 LCD. Take care to orient the ICs, diodes, electrolytic capacitors, relays and TO-220 devices correctly and note how the relay footprints support two common styles of signal relay. Regardless of relay style, the striped (coil) end faces to the left.

offers that facility, take a picture or two and check them well. We have a reasonably inexpensive binocular microscope in our lab which is brilliant for finding pesky shorts.

While you're at it, also check that all the device pins and leads have a proper fillet from the lead down to the PCB pad. It's relatively easy to get the solder to stick to a pin but not flow onto the pad, or vice versa, especially if you don't use enough flux during soldering.

If you find any problems, fix them up. You can fix bad joints by adding a dab of flux paste and then touching the tip of your iron to the junction of the device lead and PCB pad. Some small solder bridges can be solved in the same way, although it can be better (and is usually advisable) to follow up the flux paste with some solder wick (if it's saturated with solder, cut the end off and use a fresh section).

Note that there are a few unoccupied pairs of SMD pads for optional parts that we determined aren't required.

Through-hole parts

Move on to mounting all the remaining resistors. The 47Ω resistor in series with the LCD backlight can be reduced in value for more brightness, but that will reduce LED life. Or, for maximum battery life, select a higher value that provides acceptable brightness. Use good-quality resistors in the current source and references. We have provided some recommendations in the parts list.

Ensure that the high-precision 10kΩ resistor goes in the indicated location and not in place of one of the regular 10kΩ resistors.

If you don't have a 205Ω resistor, you can use 220Ω instead and replace the two parallel resistors (marked as 47kΩ and 1.5MΩ) with two 5.6kΩ resistors to get reasonably close to the required values.

Next, fit the diodes, making sure that the cathode stripes face as shown in each case. Start with the 1N4148s, then the BAT85. Be careful here – a BAT85 looks a lot like a 1N4148, but they are very different.

Then install the 1N4004 and 1N5819 diodes. They are similar sizes, so don't mix these up either.

Now is a good time to mount the NE555 IC. It doesn't need a socket, and once again, watch its pin 1 orientation. Follow with the two tactile switches, then all the through-hole ceramic and plastic film capacitors, which are not polarised.

In case you're wondering, two of the 10nF capacitors are PPS types (adjacent to S1 in Fig.6) rather than ceramic because these need to be low-leakage types. If you can't get PPS capacitors, use the best film capacitors you can and check that they don't adversely affect high resistance readings.

Install all the headers now. Remember that for programming and SPI monitoring, headers CON4 and CON6 need to be fitted. If you are using a pre-programmed PIC, then you can fit a wire link in place of JP1. If fitting JP1, simply place the jumper on it after soldering and, unless you need to reprogram the PIC, you can leave it on permanently.

Next, fit the four BC547 (or BC546, BC548 or BC549) transistors, as well as the LM336. These are all in the same packages, so don't mix them up. Follow with the two 10kΩ trimpots, orienting VR1 as shown in Fig.6. Then install all the electrolytic capacitors, with the longer positive leads going to the pads marked with a '+' sign on the PCB. The two near the top need to be laid over as shown.

This is a good time to install the relays, for which we have provided two options. One is available from

Altronics, while the narrower type is commonly available from major suppliers such as Mouser, Digi-Key and element14. The two different outlines are shown on the silkscreening; regardless of which type you use, ensure that the striped end faces to the left as shown.

The LCD mounts via a header on the back of the board. Choose the right location for the LCD type you have. It is necessary to mount the LCD quite close to the PCB, but not so close that it touches the solder joints on the main board.

We left about a 2mm gap and put a couple of dabs of neutral cure silicone under the screen to keep it from moving. Once set, the silicone will hold everything tight.

Reducing leakage paths

At this point, the PCB should have all the parts on it.

If you have a special-purpose flux cleaner such as our favourite, Kleanium Deflux-It G^2, it's a good idea to start cleaning by spraying the board with that. Let it dissolve the flux, then dab it dry with a lint-free cloth before scrubbing it with alcohol. That will remove a lot of the residue in one easy pass, making the next step easier.

Now get some isopropyl alcohol and a good scrubbing brush to clean the PCB (we used an old toothbrush). Thoroughly clean around the reference resistors, ADC and the input buffer, taking particular care to scrub away any residual flux around the ADC. After scrubbing, wet it again with alcohol and then dab it clean with a lint-free cloth to soak up any residue.

Once you're sure the board's critical areas are clean, liberally coat the ADC and reference resistor area with a clear, protective lacquer, being careful not to spray the headers. Ideally, you should use a purpose-designed PCB conformal coating (the solder-through type is great in case you find a problem later). We want all sensitive parts of the PCB clean and sealed from moisture.

Testing

The first test is to apply power and check that the regulator outputs are correct. Prepare the battery of six AA cells. There are many options for this, but the parts list specifies two 3-cell holders, and you just need to connect them in series, negative to positive.

Also cut and mount the side switch in the box, as shown in Fig.7. The switch can be mounted at any convenient location on one side of the case; the photo overleaf shows where we placed ours.

Use masking tape to mark the drill holes for the screws; 2mm holes are a good start. Also mark and drill two holes that define the ends of the slot. These are 5mm in diameter, and once you have drilled them, use a small file to join them into a slot.

Mount the switch and then, ensuring the switch is off, wire up the battery to it (insulating any exposed joints with heatshrink tubing). Next, crimp and solder the two remaining wires into the plug housing that will go to the PCB. Don't make the leads too short; ensure there is sufficient wire length to assemble and calibrate the instrument conveniently.

Double-check the polarity as there is reverse polarity protection on the PCB, but it's a bit brutal; if wired backwards, the battery will be shunted by a 1N4004 diode.

Leave the PCB on the bench so you can make measurements easily, then plug in the battery/switch combination to the header and switch it on.

Using a multimeter set to measure low DC voltage, measure between the ground test point right at the top of the PCB, and the output tabs of REG2 (3.45-3.75V) and REG3 (4.5-5.2V). If either reading is wrong, check the input voltage at the cathode of D9, in the lower left-hand corner of the board. This should be around 8-9V.

If something is getting hot, switch off and figure out why.

If one voltage is low, carefully check the soldering of the regulator

Troubleshooting

It is normal on the first power up for a message stating that default calibration values are being loaded.

If the Meter is not working at all, check the following:

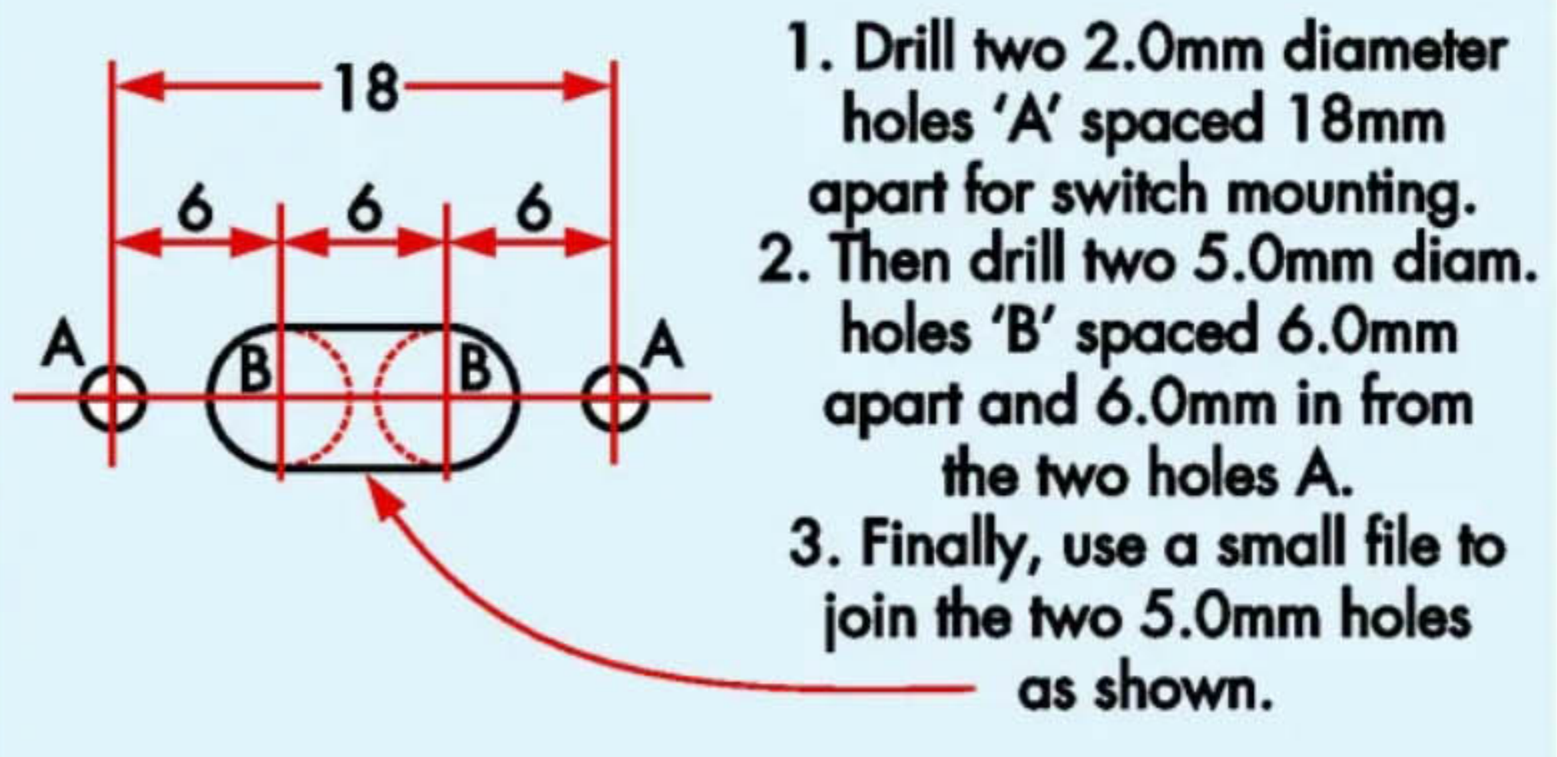
- The solder joints on all SMDs – check for improperly formed joints or solder bridges.
- The battery voltage (you should have checked this earlier).
- The regulator output voltages (ditto).

If the LCD is not displaying text:

- Can you adjust VR2 to get anything on the display?
- Is there about −2.2V at the anode of D10? If not, check around the 555 for faults.
- Check for activity on the LCD RS, RW, E and D7, 6, 5 and 4 lines (the rest are not used) on the LCD header. If these are not active, check the soldering on the microcontroller and verify that it has been programmed.
- If there is a problem with the ADC, there will be a message on the LCD telling you that. In this case, check the soldering on the ADC chip. Also check the SPI lines with a scope for activity. You should see activity on the CS, MCLK, SDI and SDO lines. The absence of activity suggests a short or similar problem.

If it appears to be working, but the measurements are wrong:

- The connections for Sense+, Sense–, Force+ and Force–. If you have these swapped, the Meter will not make sensible measurements.
- Are the relays clicking? If not, look at the ADC connections again. Look at the four digital output lines and also make sure you have used proper BC54x transistors and the pinouts are correct. We have heard about some parts labelled BC54x that use the wrong pinout.
- Have you used relays with 5V DC coils?
- Are the reference resistors the correct values?
- Connect an ammeter on its 200mA range or similar from pin 3 of IC3, the LT3092 (the one closest to the top of the board) to the anode of D3, with the sense lines shorted (eg, using a jumper). You should measure very close to 50mA, then if you remove the short on the sense lines, it should drop to 0.5mA.
- Check that the 2.5V reference voltage is right; you should have checked this while adjusting it.
- Check that you put those push buttons in the right way around; if you rotated them by 90°, they would be shorted 'on' and you are probably stuck in calibration mode and keep getting calibration messages, but the buttons won't work!



1. Drill two 2.0mm diameter holes 'A' spaced 18mm apart for switch mounting.
2. Then drill two 5.0mm diam. holes 'B' spaced 6.0mm apart and 6.0mm in from the two holes A.
3. Finally, use a small file to join the two 5.0mm holes as shown.

Fig.7: the on/off slide switch can be placed along any convenient edge of the case. Apply this template, drill the two mounting holes plus 5mm holes at either end of the slot outline, then file away the material between those holes.

You can download it from the September 2023 page of the PE website at: https://bit.ly/pe-downloads

and its surrounding components and verify that the components are the right types and oriented correctly. Verify that you have not put the LT3092 in place of a regulator.

Assuming they check out, verify that the LCD backlight is on, then adjust 10kΩ trimpot VR2 until text shows on the screen.

Now it is time to calibrate the 2.5V reference, which also optimises its stability. Monitor the voltage across TP1 and TP2, in between the holes for the test terminals on the PCB. Adjust 10kΩ trimpot VR1 to get a reading as close to 2.50V as possible. This does not need to be super precise, but get it close.

At this point, all the adjustments on the PCB are finished, and when you switch it on, the relays should click, and a message saying 'Over Range, Check Sense Conn' should come up on the screen. You will find that the Meter is now working but not fully calibrated.

Mounting it in the case

The PCB is designed to fit into the Altronics H0401 instrument case. The front panel drilling and cutouts are in Fig.8. You will have already mounted the slide switch.

There are four holes for the Kelvin probes binding posts/banana sockets. The specified binding posts include standard 3mm banana sockets. These holes line up with the large holes in the PCB, allowing the wiring to run straight through. There are also four countersunk holes for M3 screws used to mount the PCB.

The front panel covers the PCB mounting holes, so we were careful to countersink the screw heads to be flush with the front panel.

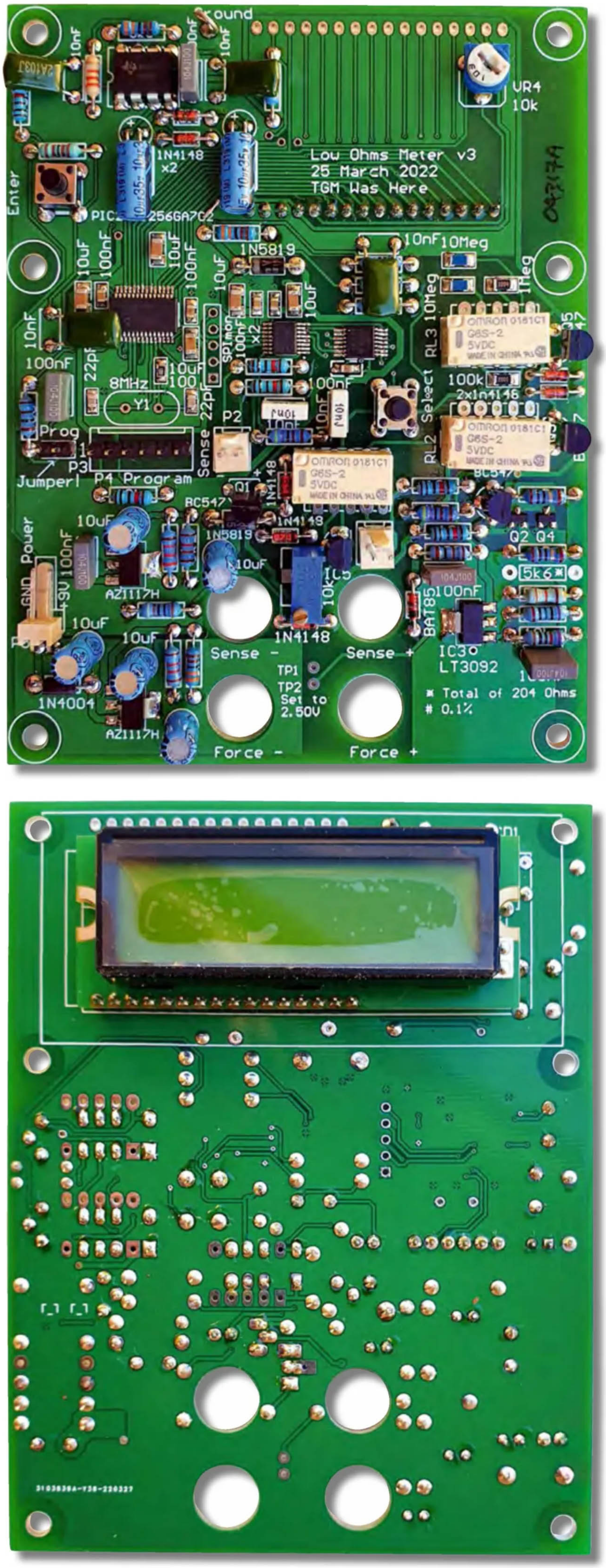
The smaller LCD cut-out shown matches the LCD we used. An alternative cut-out is shown for another common type. Before cutting, check which hole suits your LCD module. There could be a third option, in which case you'll have to figure out the location and size of this cut-out.

Internally, the case preparation is simple. By keeping the LCD mounted close to the PCB, the LCD will sit neatly behind the clear opening in the laminated label.

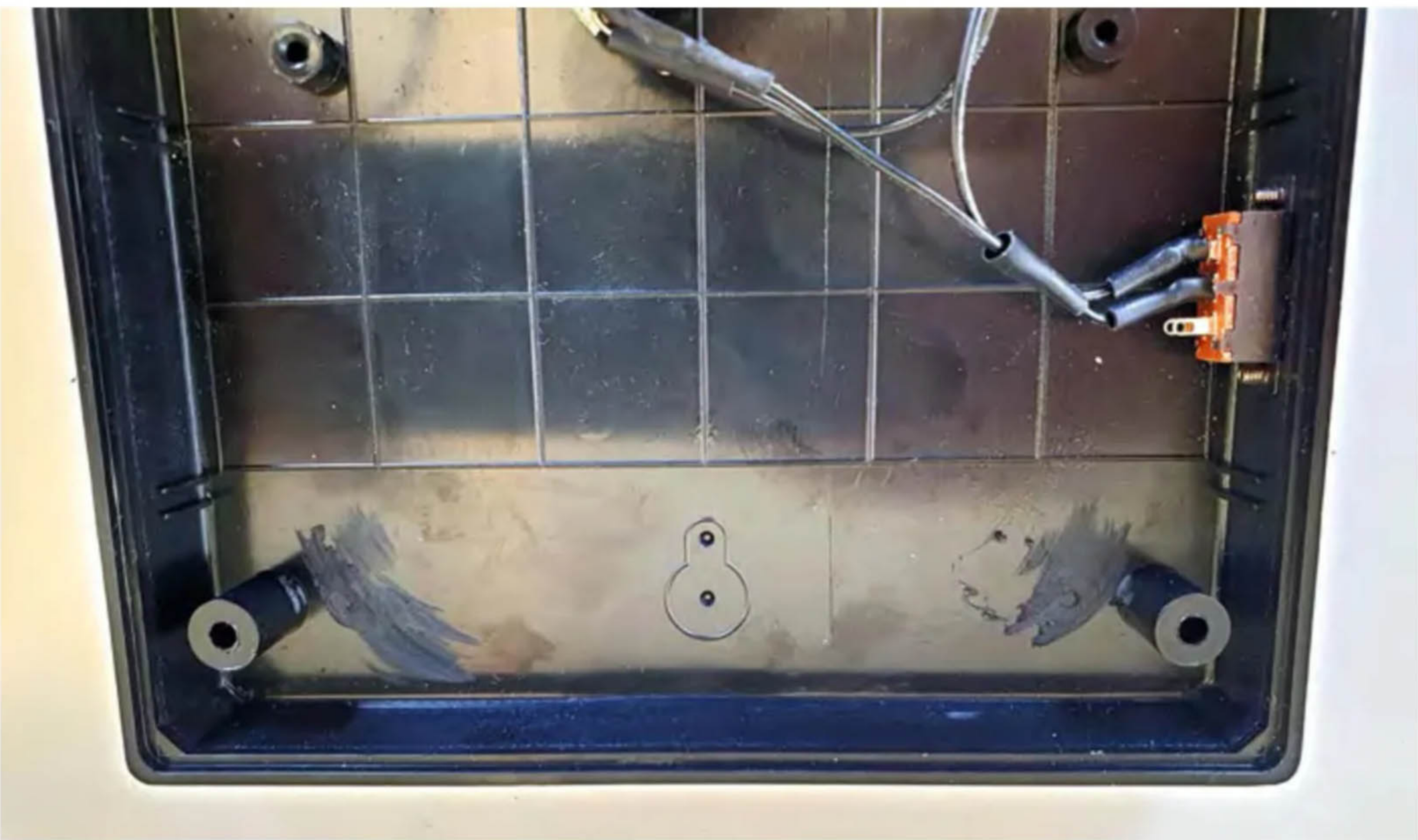
Fix the cell holders inside the base with either a dab of neutral cure silicone sealant or double-sided tape. To allow the PCB to fit, we cut off the two standoffs at the top of the base so we could line up the battery holders along the top, as shown in the photo published last month.

There is minimal wiring involved in preparing the case. The power, Force and Sense connections all use pluggable headers. Start with two pairs of red/black wires 150mm long, and crimp these to the pins that match the polarised header plugs.

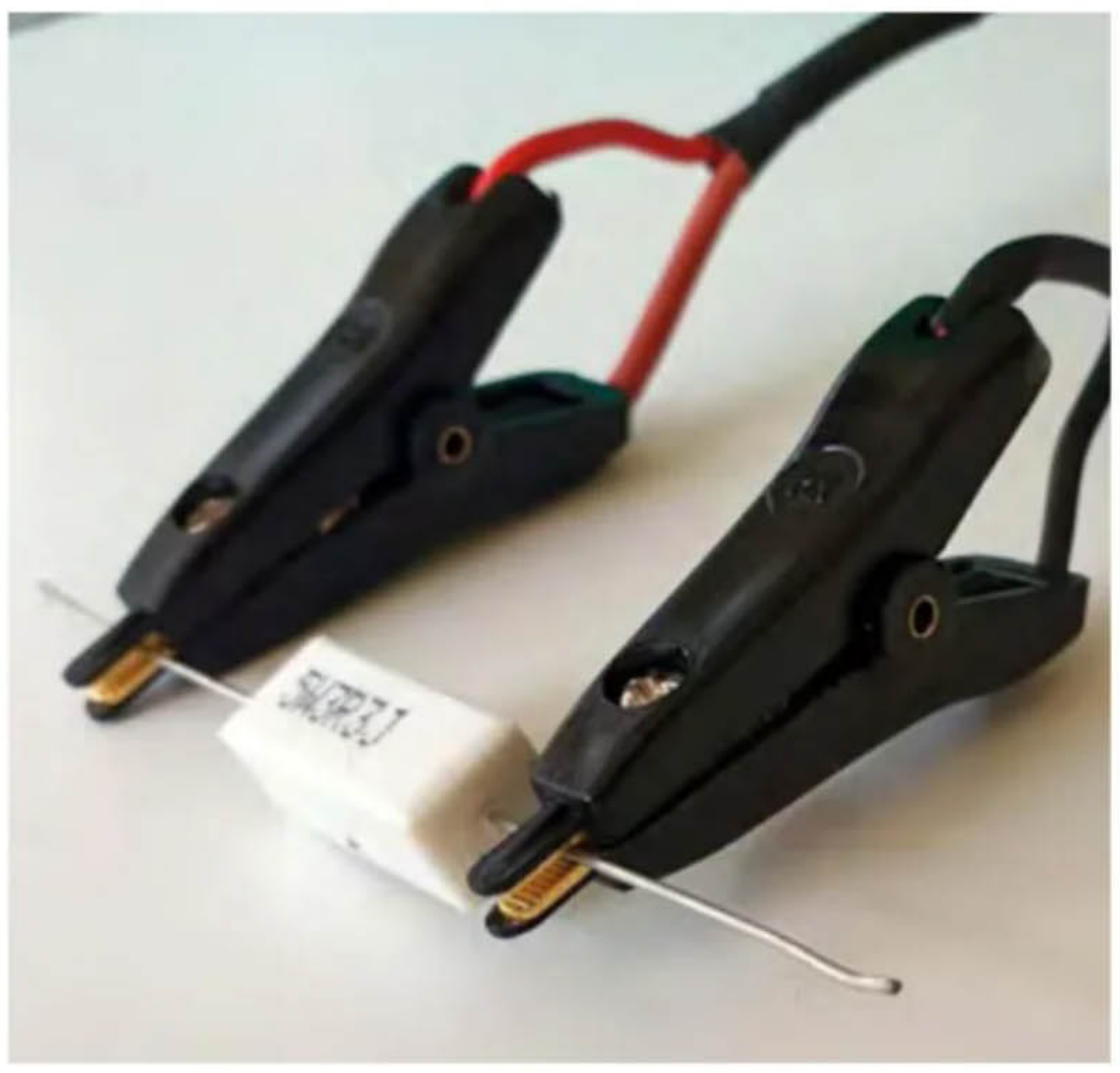
Note that the + and – pins are swapped between the Force and Sense headers. The easiest solution is to simply insert these in the plastic blocks last, ensuring they line up



Front and rear shots of the Ohmmeter PCB. At the rear, two different types of 16x2 LCD modules can be fitted, as the ones found online typically come in one of two sizes.



Left: this shows where we mounted the on/off slide switch on our prototype.



Above: measuring a 3.3Ω enclosed wirewound ceramic core resistor.

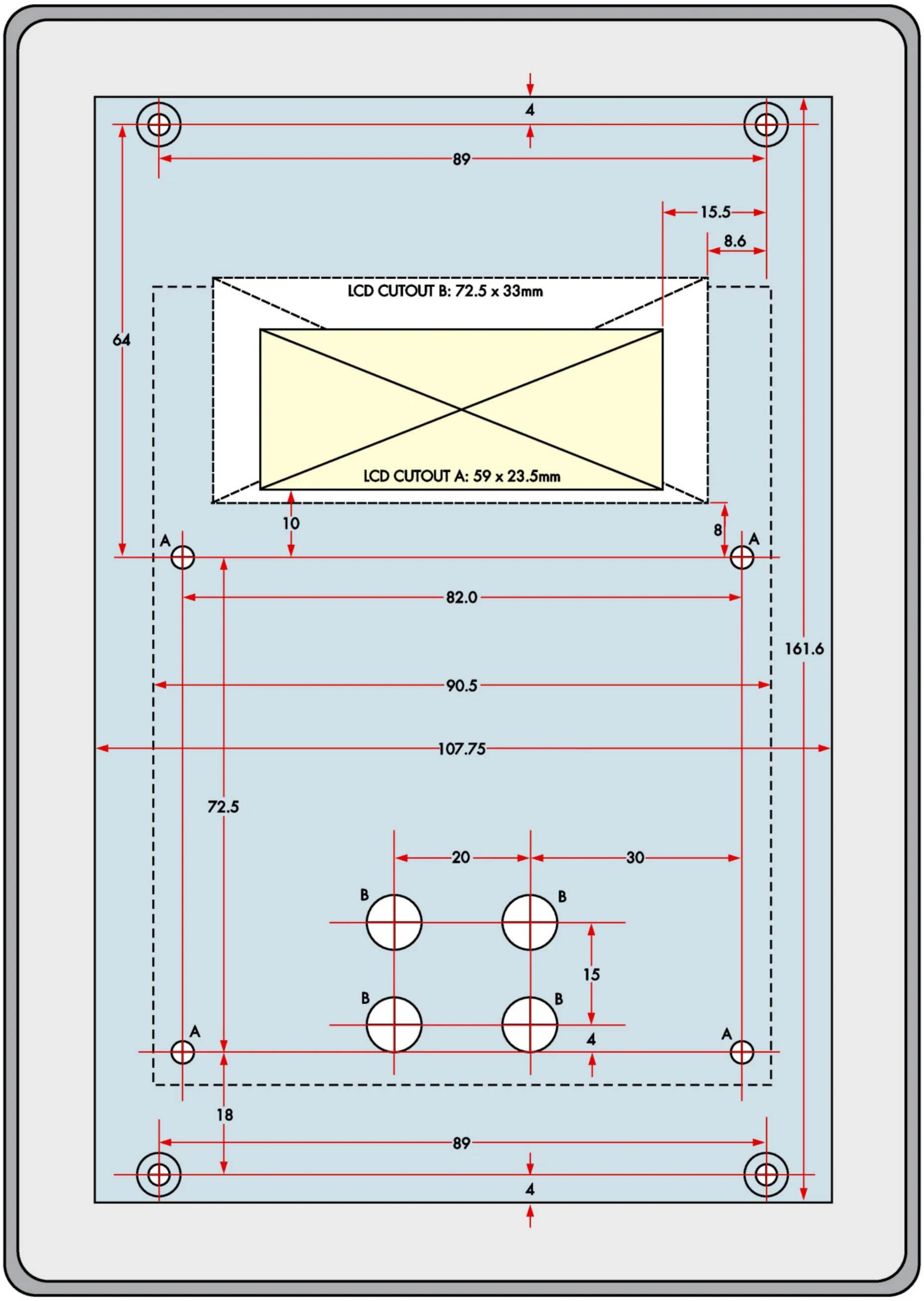

VIEW INSIDE FRONT PANEL
ALL DIMENSIONS IN MILLIMETRES
HOLES A: 3.0mm DIAM.
HOLES B: 8.0mm DIAM.
4
89
15.5
8.6
LCD CUTOUT B: 72.5 x 33mm
LCD CUTOUT A: 59 x 23.5mm
64
10
8
A
A
82.0
161.6
90.5
107.75
72.5
20
30
B
B
15
B
B
4
A
A
18
89
4

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Fig.8: these drilling/cutting templates fit on the inside of the case front panel.

Select the one which lines up with your LCD screen. You can download the template from the September 2023 page of the PE website at: https://bit.ly/pe-downloads

Print them out, then cut them up and stick them onto the panel so you can accurately mark the locations of the holes.

with the silkscreened markings on the PCB.

We printed the front panel label onto thick paper and cut out the hole for the LCD. You can download the artwork as a PDF from the September 2023 page of the *PE* website at: **https://bit.ly/pe-downloads**

There are two versions to suit the display window locations for two common types of compatible LCD screens, as shown in Fig.9.

We then laminated this and used a sharp knife to cut out the holes for the banana plugs. The laminate makes a simple and effective window for the LCD. After that, we stuck it onto the front of the case with a very thin layer of neutral cure silicone sealant.

Calibration

The calibration procedure has been deliberately kept simple. There is one adjustment per range, which is stored in flash memory and loaded on power-up. As you need access to pushbutton switches S1 and S2 for calibration, it can only be done with the case open.

Start calibration by pressing the ENTER key (S2) on the PCB until a calibration message comes up. The button press detection for the user interface is not terribly fast; buttons are checked after each ADC measurement, or about four times a second. Keep that in mind while calibrating the unit.

The calibration process generates a correction for each range independently of all other ranges. Start by connecting a calibration resistor to the Meter as if you were measuring its value. The values used should ideally be close to the top of each range (as specified in the parts list last month and in Table 1).

Once the resistor is connected, you adjust the calibration up/down until the Meter reads the correct value of the calibration resistor. You then accept the calibration value for that range. Once all ranges have been calibrated, the data is saved, and the Meter reverts to normal operation.

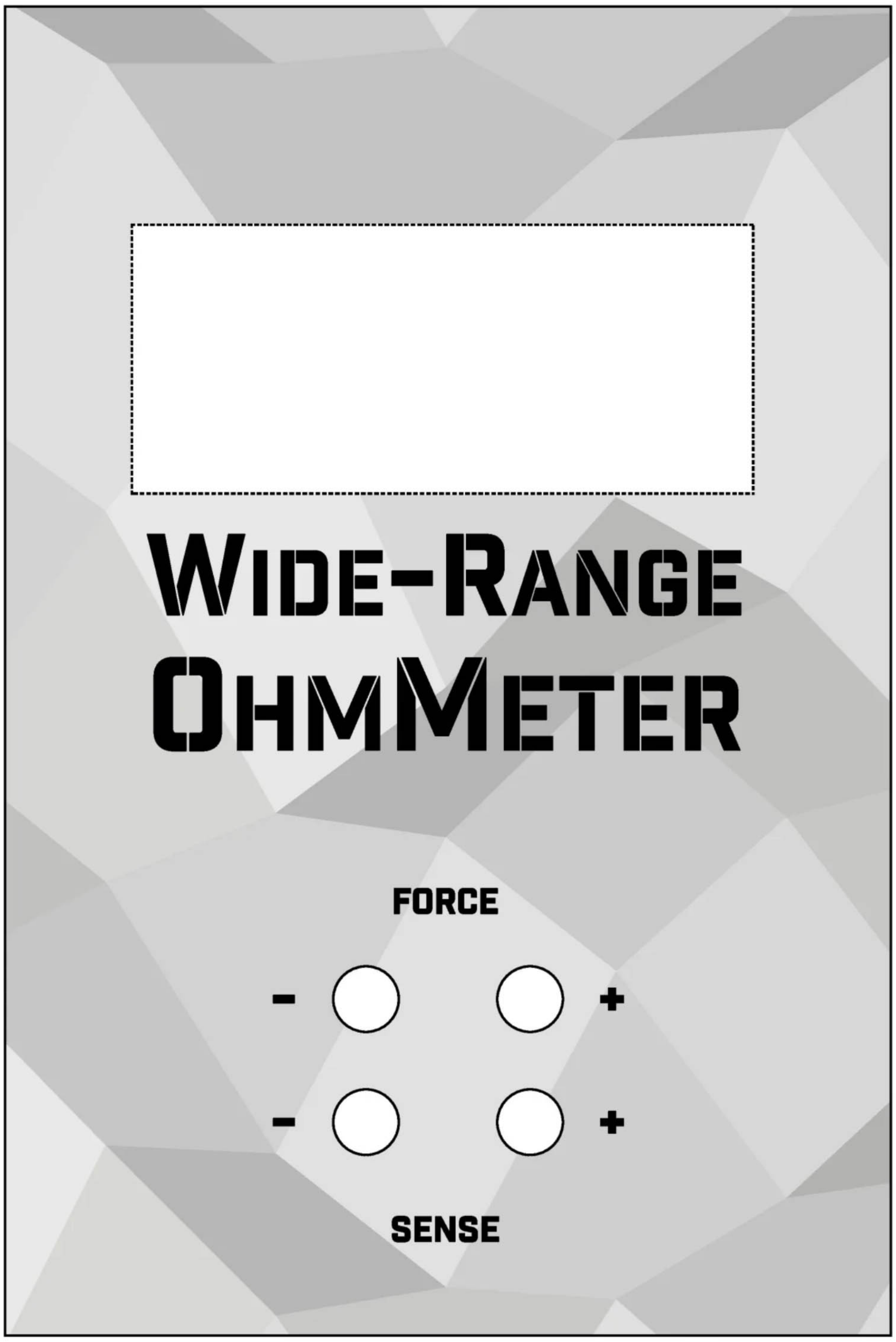

Fig.9: while the instrument is simple enough that you might get away without a front panel label, it does make it look quite a bit nicer. Once again, select the one that matches your LCD panel position. Cutting out the LCD rectangle before laminating it produces a protective window for the LCD screen.

The Meter has five ranges, shown in Table 1, along with the recommended calibration resistors. All but the 10MΩ types have ±0.1% tolerances, and most are less than 50p. If you're going to use different calibration resistors, they should ideally have tolerances of ±0.1% or better and temperature coefficients no higher than 50ppm/°C.

On each range, the Meter will prompt you for a calibration resistor. Once you clip the resistor onto the

Table 1 – ranges and calibration

Range	Calibration resistor	Suitable test resistor	Notes
0-30Ω	YR1B27R4CC (27.4Ω ±0.1%)	YR1B10RCC (10Ω ±0.1%)	A few test resistors in the 20mΩ-220mΩ range would be handy
30Ω-3kΩ	YR1B2K94CC (2.94kΩ ±0.1%)	YR1B1K0CC (1kΩ ±0.1%)	
3kΩ-100kΩ	YR1B97K6CC (97.6kΩ ±0.1%)	YR1B100KCC (100kΩ ±0.1%)	
100kΩ-1MΩ	YR1B976KCC (976kΩ ±0.1%)	YR1B1M0CC (1MΩ ±0.1%)	
1MΩ-20MΩ	MF0204FTE52-10M (10MΩ ±1%)		High-precision resistors in this range are very expensive

Meter, it will present readings. Make adjustments as follows:

1. If no button is pressed, the Meter will continually update the measured resistances.
2. When the SELECT button (S1) is pressed:
   - a You will see either a < or > symbol to the right of the measured value.
   - b The > indicates you will increase the calibration factor and the presented value.
   - c Similarly, < indicates you will reduce the calibration factor.
   - d To reverse the direction, hold down the SELECT button and then press ENTER (S2) briefly at the same time.
   - e Pressing SELECT changes the calibration factor and thus the displayed value in the direction shown.
   - f The longer you hold the SELECT button, the faster the calibration corrections change. To slow the rate of change down, release the SELECT button for a second. There are three speeds – the slowest will allow tiny corrections, while medium and fast speeds let you get to the required value quicker.
3. If the ENTER button is pressed alone, it will accept the current calibration value and move to the next range.
4. After all adjustments are completed, the calibration data is saved, and the Meter goes back to normal.

Accuracy and precision

Our tests show that the precision of this Meter between about 10mΩ and 10MΩ is entirely defined by the calibration precision. We calibrated the prototype using the recommended reference resistors and achieved precision close to ±0.1% across most of the range. The better calibration you can give it, the better performance you will achieve.

Repeatability across our five prototype meters is excellent, indicating good linearity of the ADCs. We have gone to great lengths to ensure stability over time and temperature, so it should remain stable once calibrated.

You will notice that the meter displays more significant digits than the precision would indicate.

The Meter is very stable and, in most ranges, provides noise-free measurement to a resolution of much better than 0.1%.

While the accuracy is limited to about 0.1%, the resolution and short-term repeatability are much better than this. So if you want to match resistors to a high precision, the Meter provides the extra resolution you need for that.

Using it

It's just a matter of switching it on, connecting the device to be measured and reading off the value.

At start-up, it shows the firmware revision and the measured battery voltage. If the battery falls below 6.5V, it will ask for a new set.

Try not to leave the Meter on for hours at a time, since it does draw some current, especially in the low range. Aside from this, we believe this will become a handy tool for your workbench.

We do not expect the Meter to need calibrating all that often. We went to a fair bit of bother to make sure things should stay stable. Still, keep those calibration resistors and clip them on once a year or so. If you are making a critical measurement, a quick check will only take you a second or two.

When measuring low-value resistances, on the order of a few milliohms, component lead resistance can become significant. So connect the test clips as close to the body of the device as possible.

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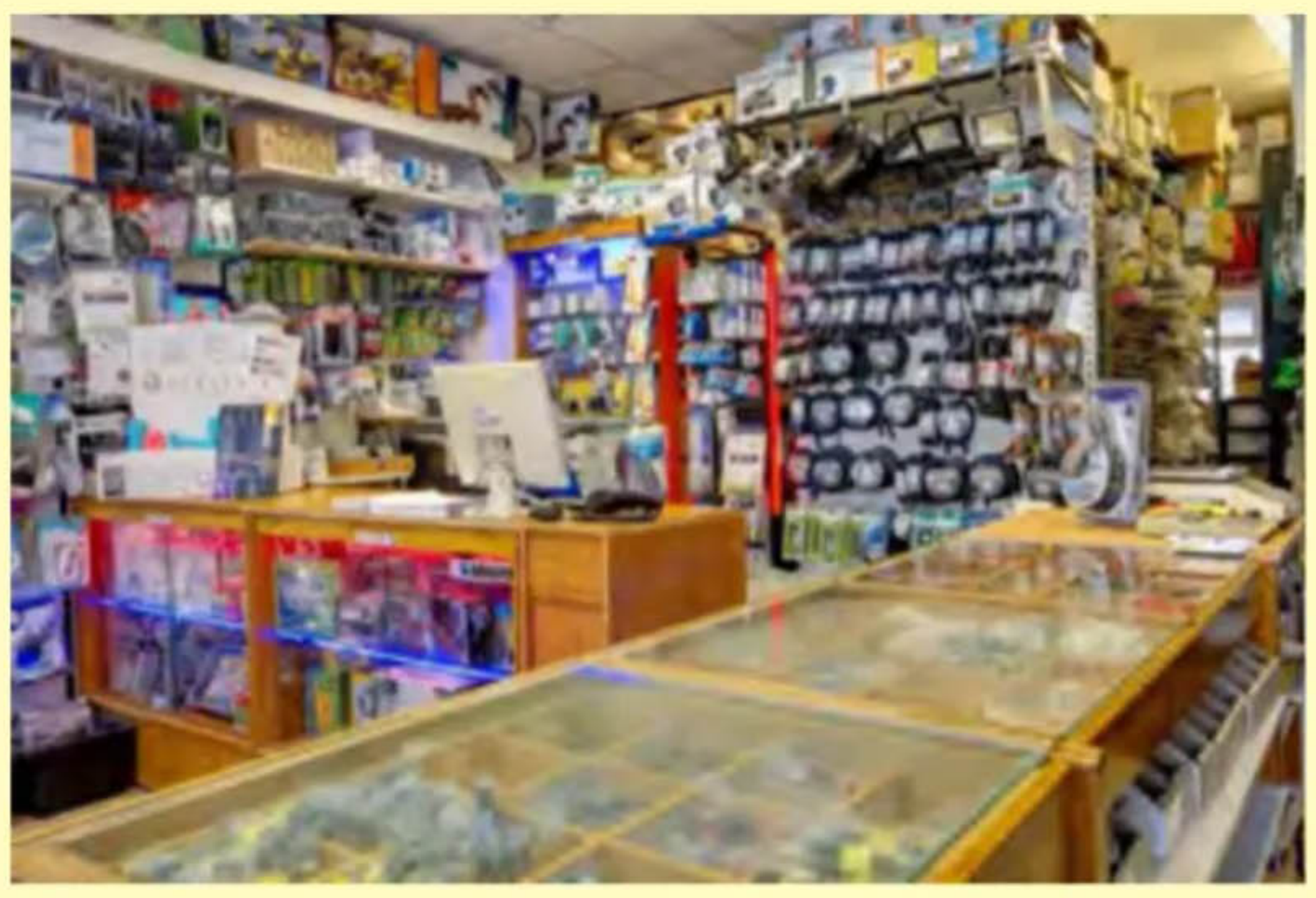

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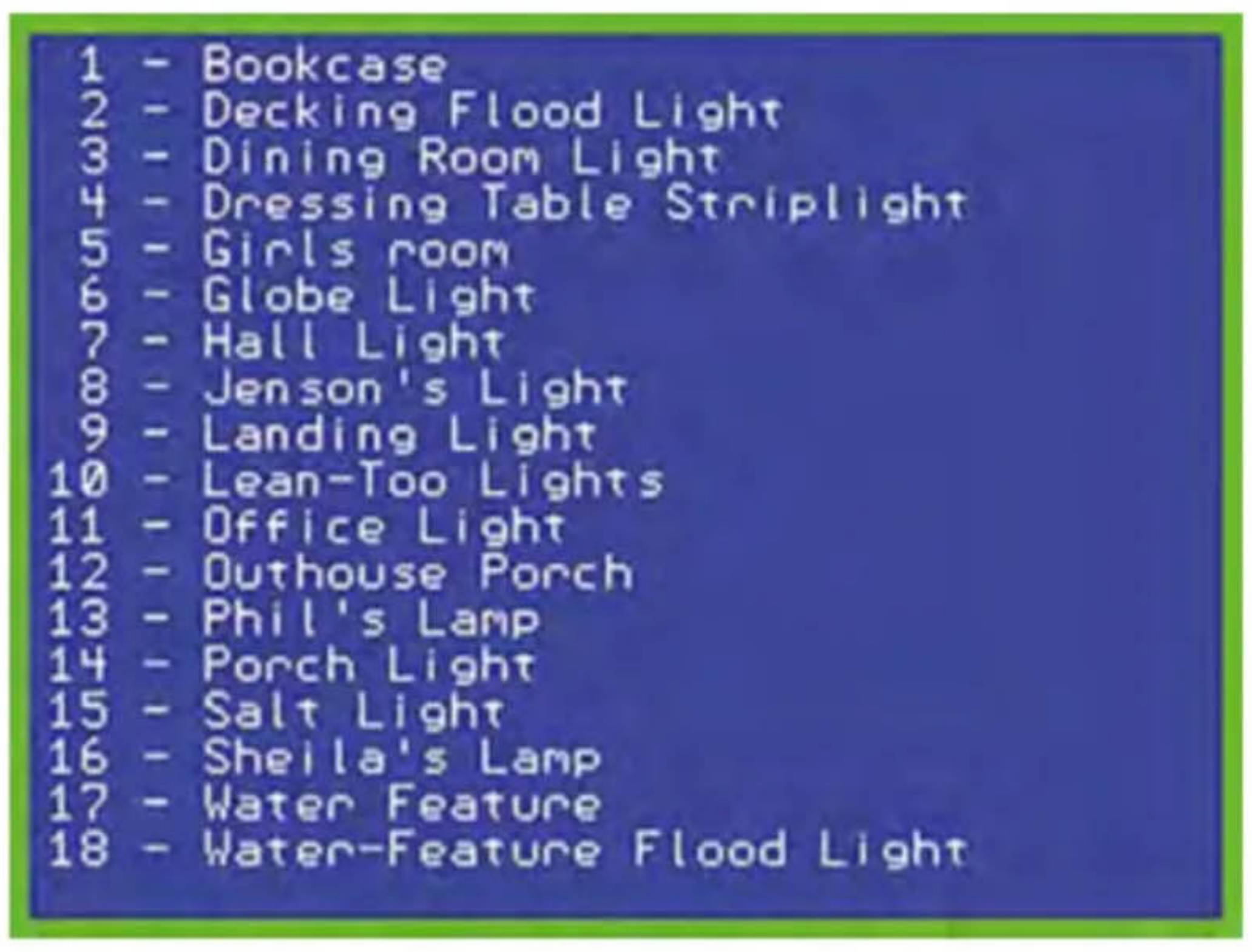
Make it with Micromite

Phil Boyce – hands on with the mighty PIC-powered, BASIC microcontroller

Part 49: PicoMite Smart light Controller – Part 4

Last month, we covered extracting a list of available smart lights (and smart sockets) from a Hue Hub, and then how to sort them all alphabetically by name – see Fig.1. These names were passed in the JSON data that the PicoMite received from the Hue Hub once an initial request was sent by our demo code. In addition to the names, we also extracted other information, such as the current smart light state (on or off), each smart light's unique ID number, and also, for any smart light with dimmable functionality, the last setting of the brightness level.

This month, we conclude the project with some program code that allows control of selected smart lights via the PicoMite's touchscreen. We will not go into every detail of the code, but instead we will discuss the process flow of the key functions, remembering that the initial concept was to allow a user to have access to control a limited number of lights, rather than be able to control all the lights in the setup. For example, in my specific case it was to allow my children to only be able to control the lights in their individual bedrooms, and not be able to annoy their siblings (and parents!) by being able to control every single light throughout the house.



```
 1 - Bookcase
 2 - Decking Flood Light
 3 - Dining Room Light
 4 - Dressing Table Striplight
 5 - Girls room
 6 - Globe Light
 7 - Hall Light
 8 - Jenson's Light
 9 - Landing Light
10 - Lean-Too Lights
11 - Office Light
12 - Outhouse Porch
13 - Phil's Lamp
14 - Porch Light
15 - Salt Light
16 - Sheila's Lamp
17 - Water Feature
18 - Water-Feature Flood Light
```

Fig.1. The **ExtractJSON.txt** program from last month displays an alphabetically sorted list of all available smart lights (and smart sockets) on the PicoMite's Touchscreen.

The project's required program code (**PicoMiteSLCv2.txt**) is available for download from the September 2023 page of the *Practical Electronics* website at: **https://bit.ly/pe-downloads**

Remember, as always, the program code presented is provided to you as a working minimum for you to build upon. You can easily customise it so that it looks and works the way you want it to. In addition, we would encourage you to add new features so that the PicoMite smart light controller meets your specific needs; some ideas will be discussed at the end. On the other hand, you may simply wish to use this controller with your Hue setup as an alternative to the standard Hue switches and buttons.

Functional requirements

To allow control of certain specific smart lights (and smart sockets) in the home, the program code should provide the following capabilities:

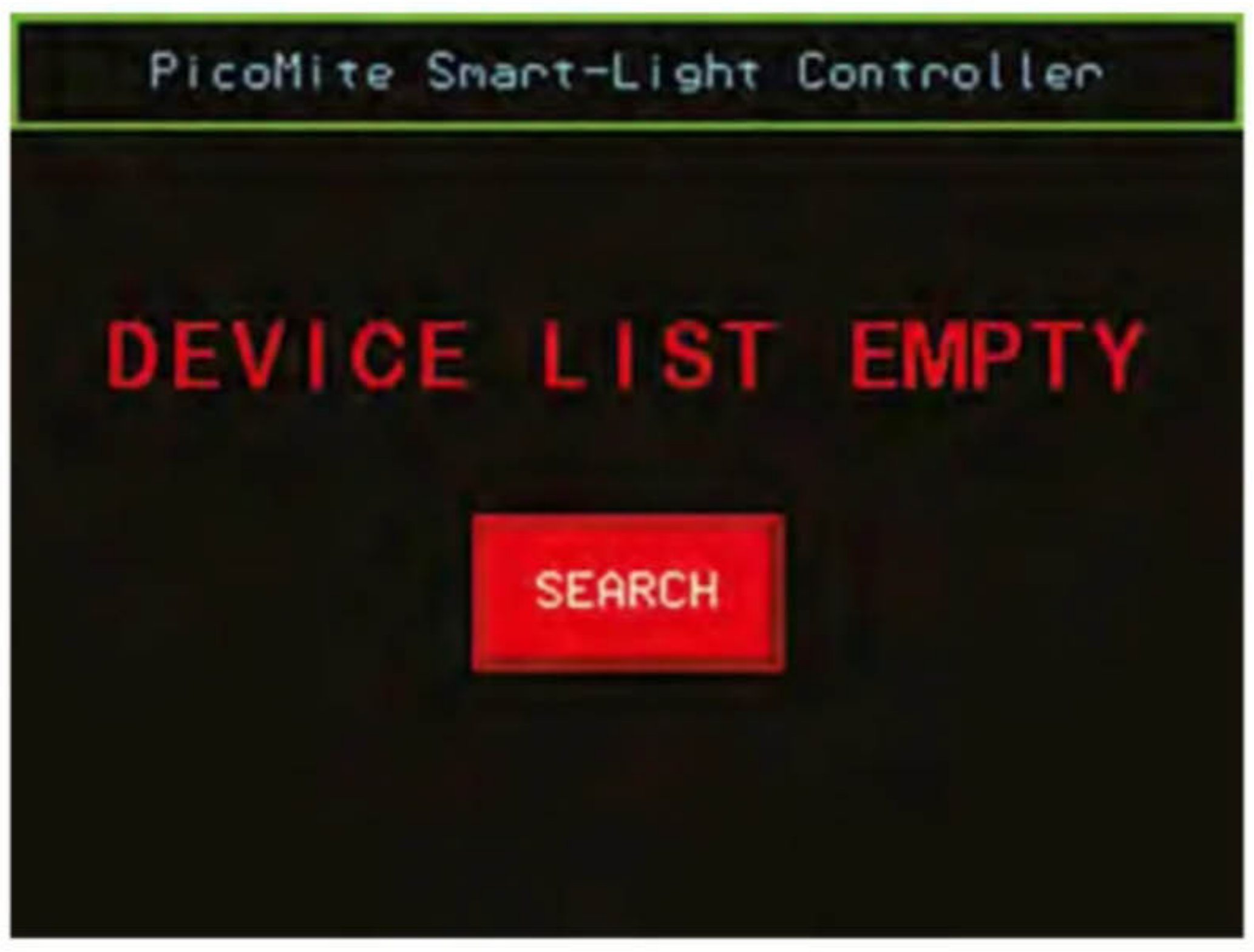
- Allow an admin user (eg, parent) to:
  1. Fetch the most recent data from the Hue Hub for all smart lights and smart sockets.
  2. See an alphabetically sorted list of names for all smart lights and smart sockets. If the list is too long for the touchscreen, then show it on multiple pages.
  3. Select which smart lights and smart sockets non-admin user(s) may control. Selection is made using a 'tick box' against each name.
  4. Refresh data from the Hue Hub if new devices are added to the setup.

- Allow a non-admin user (eg, child) to:
  5. See only a chosen subset of names for the smart light(s) and smart socket(s) selected by the admin user – again, if the list is too long then use multiple touchscreen pages.
  6. Switch any smart device ON or OFF by pressing the appropriate button – two buttons against each name in the user's list.

In the six key points listed above, there will also need to be quite a lot of error-trapping. For example, in point 3 (admin user selecting which devices a user can control), if nothing has been selected, then a warning message will need to be shown. To make the above clear, let's work through each of these key points in turn.

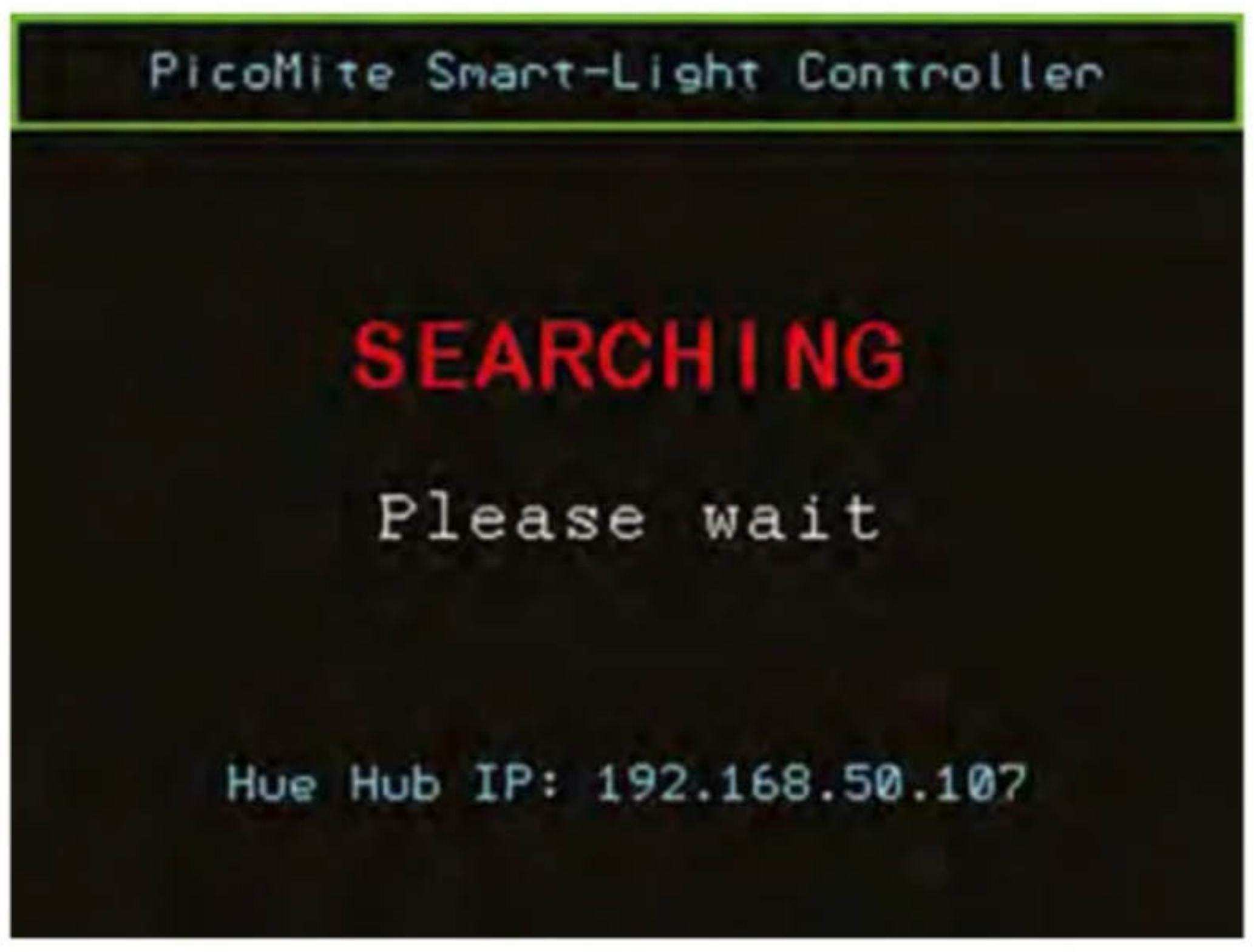
1. Fetch data

On running the program code, the PicoMite will not contain any device information (ie, no names for smart lights or smart sockets). Therefore, the user is prompted to search for devices – see Fig.2. After pressing the 'Search' button, a request is sent to the Hue Hub, and a 'Please wait' message will be displayed while the request and response is processed – see Fig.3. The request sent,


PicoMite Smart-Light Controller

DEVICE LIST EMPTY

Fig.2. When the program code is `RUN`, the PicoMite will need to search for a list of devices – this is manually triggered.


PicoMite Smart-Light Controller

SEARCHING

Please wait

Hue Hub IP: 192.168.50.107

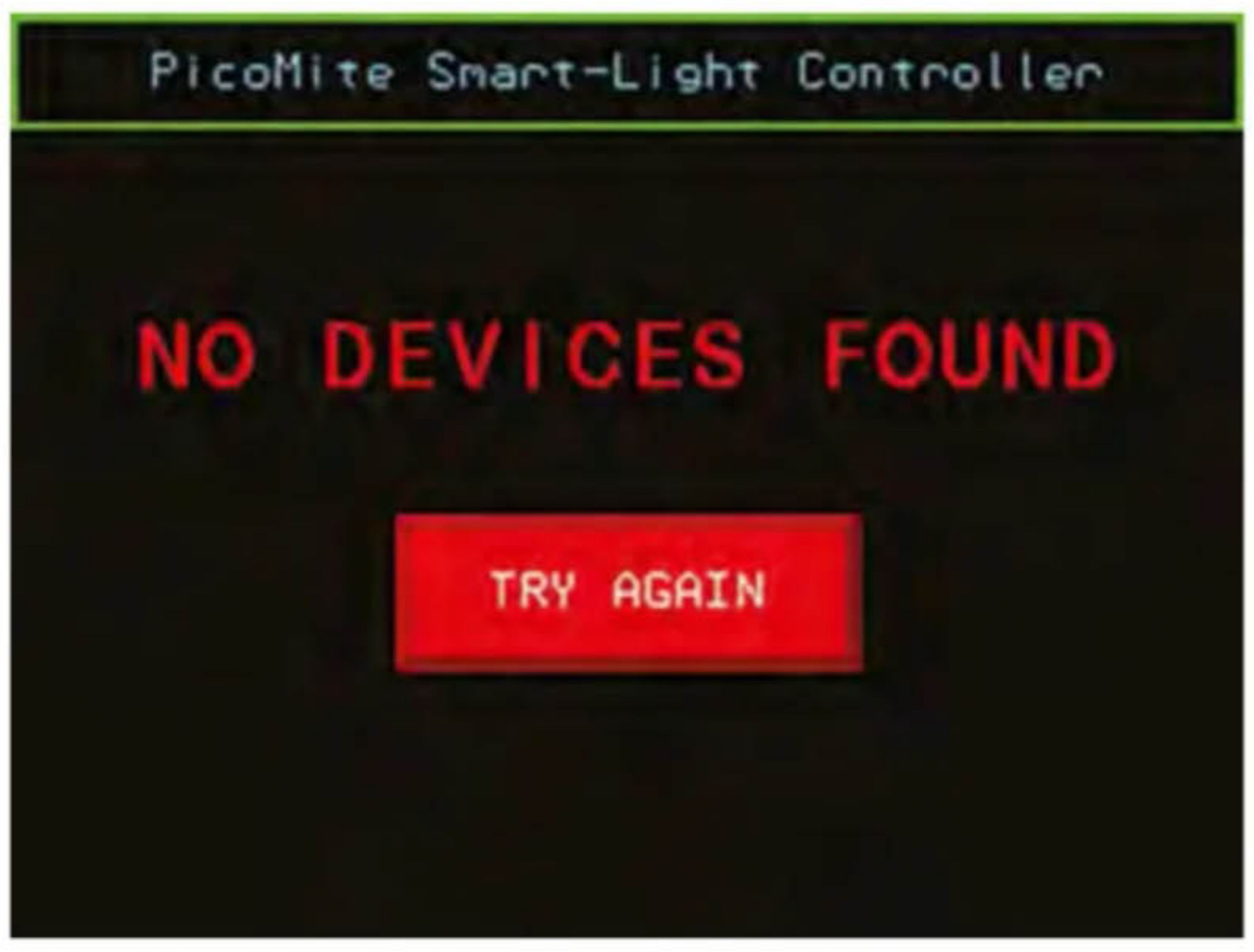
Fig.3. After the search request is sent to the Hub, and while any JSON response is processed, this screen is displayed. Note the Hub's IP address is displayed at the bottom of the screen.

and the processing of the response back, is based on the **ExtractJSON** code from last month. If no devices are detected then the variable `L_DeviceQty` will have a value of `0`, resulting in the warning message shown in Fig.4. In this situation, a 'Try Again' button will allow the admin user to repeat the process. If the value of `L_DeviceQty` is greater than `0`, then its value will represent the number of devices that are configured in the Hue Hub.

2. Admin list (all devices)

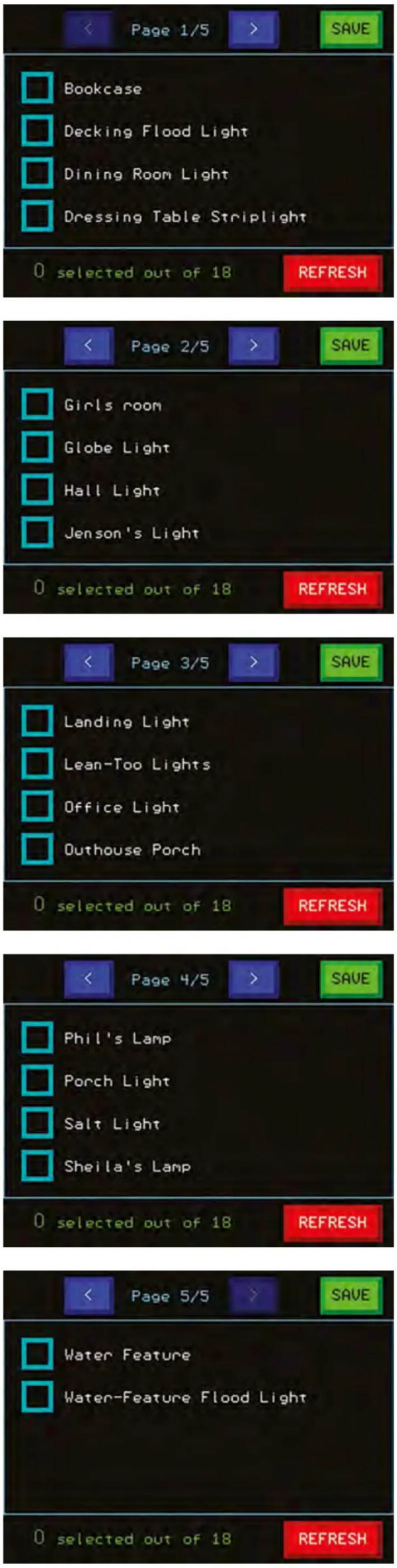
Once valid information has been received from the Hue Hub, the names of all smart devices will be displayed alphabetically on the touchscreen – see Fig.5a-e. There are a few things to point out on this screen:

- If the list contains more than four devices, then there will be multiple pages (only four devices are displayed per page). Figures 5a-5e show the five pages required to display the 18 smart devices as shown listed in Fig.1.
- A page navigator is located at the top of the touchscreen, comprising the blue '<' and '>' buttons. Note that the current page number and the total number of pages is also displayed (ie, 'Page 1/5' means the touchscreen is showing the first page of five pages).


PicoMite Smart-Light Controller

NO DEVICES FOUND

Fig.4. If no smart devices are found after the JSON processing, this screen is displayed, with an option to 'Try Again'.



☐ Bookcase
☐ Decking Flood Light
☐ Dining Room Light
☐ Dressing Table Striplight

0 selected out of 18

☐ Girls room
☐ Globe Light
☐ Hall Light
☐ Jenson's Light

0 selected out of 18

☐ Landing Light
☐ Lean-Too Lights
☐ Office Light
☐ Outhouse Porch

0 selected out of 18

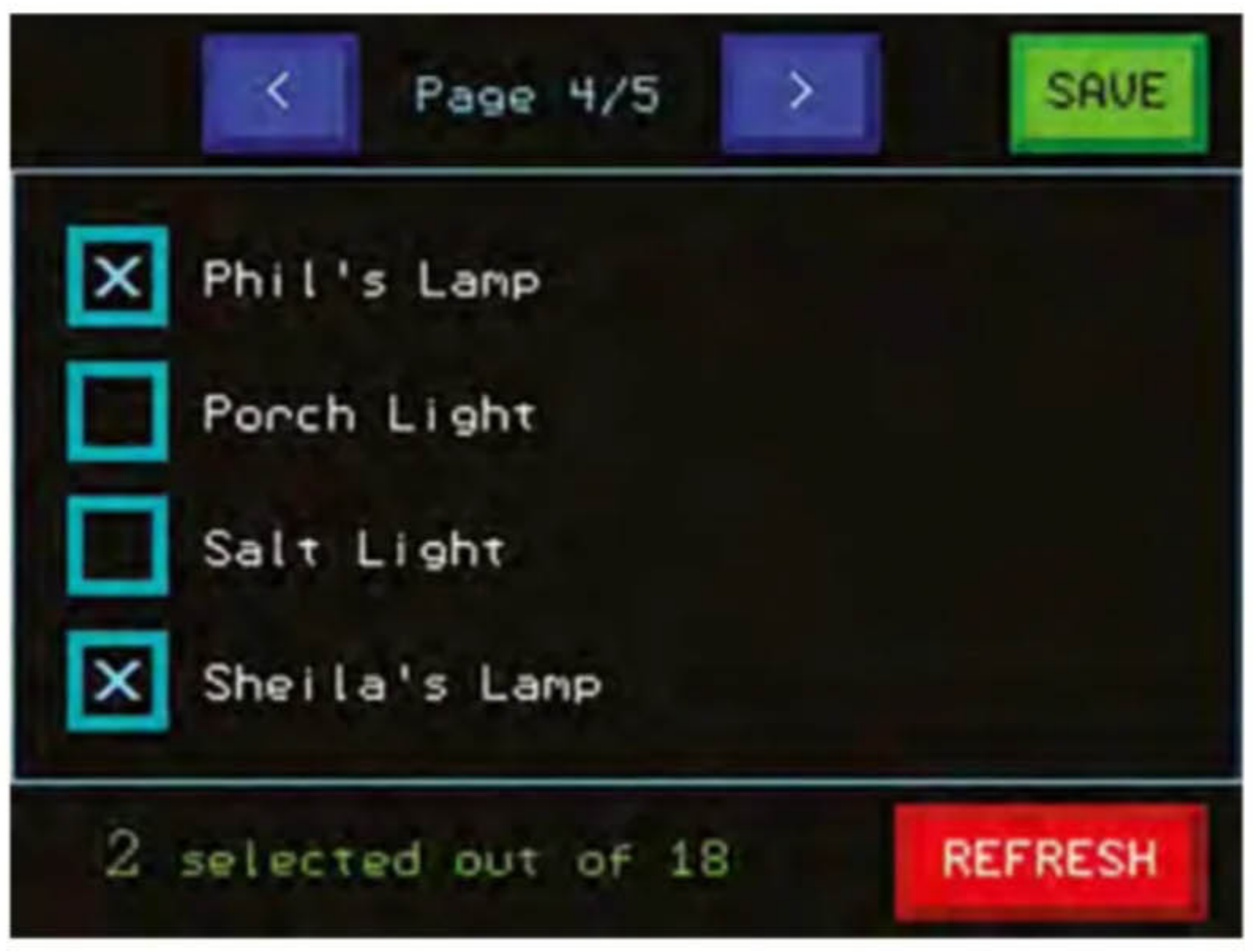
☐ Phil's Lamp
☐ Porch Light
☐ Salt Light
☐ Sheila's Lamp

0 selected out of 18

☐ Water Feature
☐ Water-Feature Flood Light

0 selected out of 18

Fig.5a-5e (top to bottom). Controllable smart devices that have been configured in the Hue App will be listed alphabetically on the 'selection screen'. Four smart devices are listed per page, meaning that five pages are needed to list all 18 devices from Fig.1. Note the blue page navigator at the top, the green 'Save' button and the red 'Refresh' button.



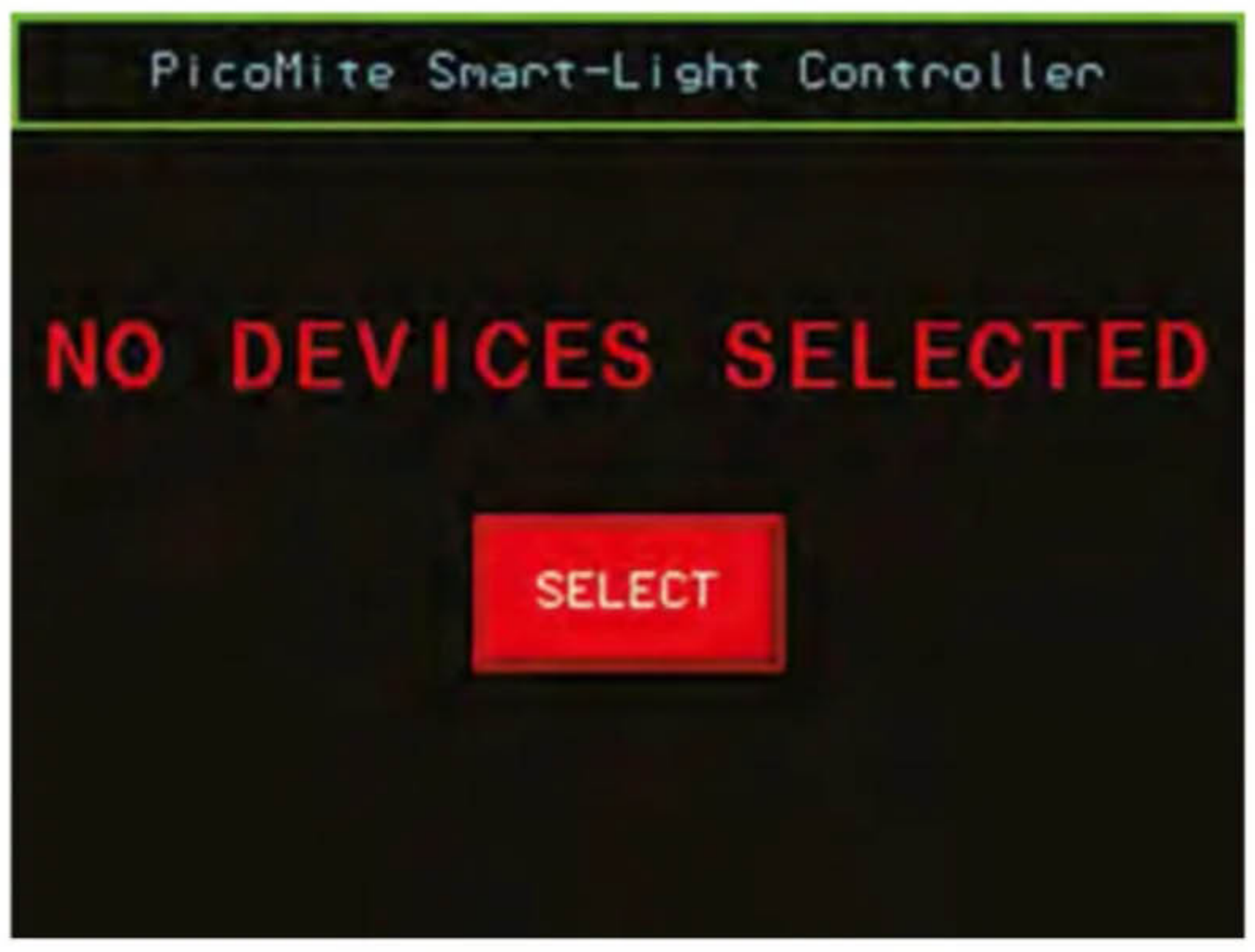
☒ Phil's Lamp
☐ Porch Light
☐ Salt Light
☒ Sheila's Lamp

2 selected out of 18

Fig.6. Here, two smart devices have been selected ('Phil's Lamp' and 'Sheila's Lamp') as indicated by the 'X' in the adjacent tick box. Note that the count of the total number of smart devices selected (from all pages) is shown in green at the bottom of the screen.

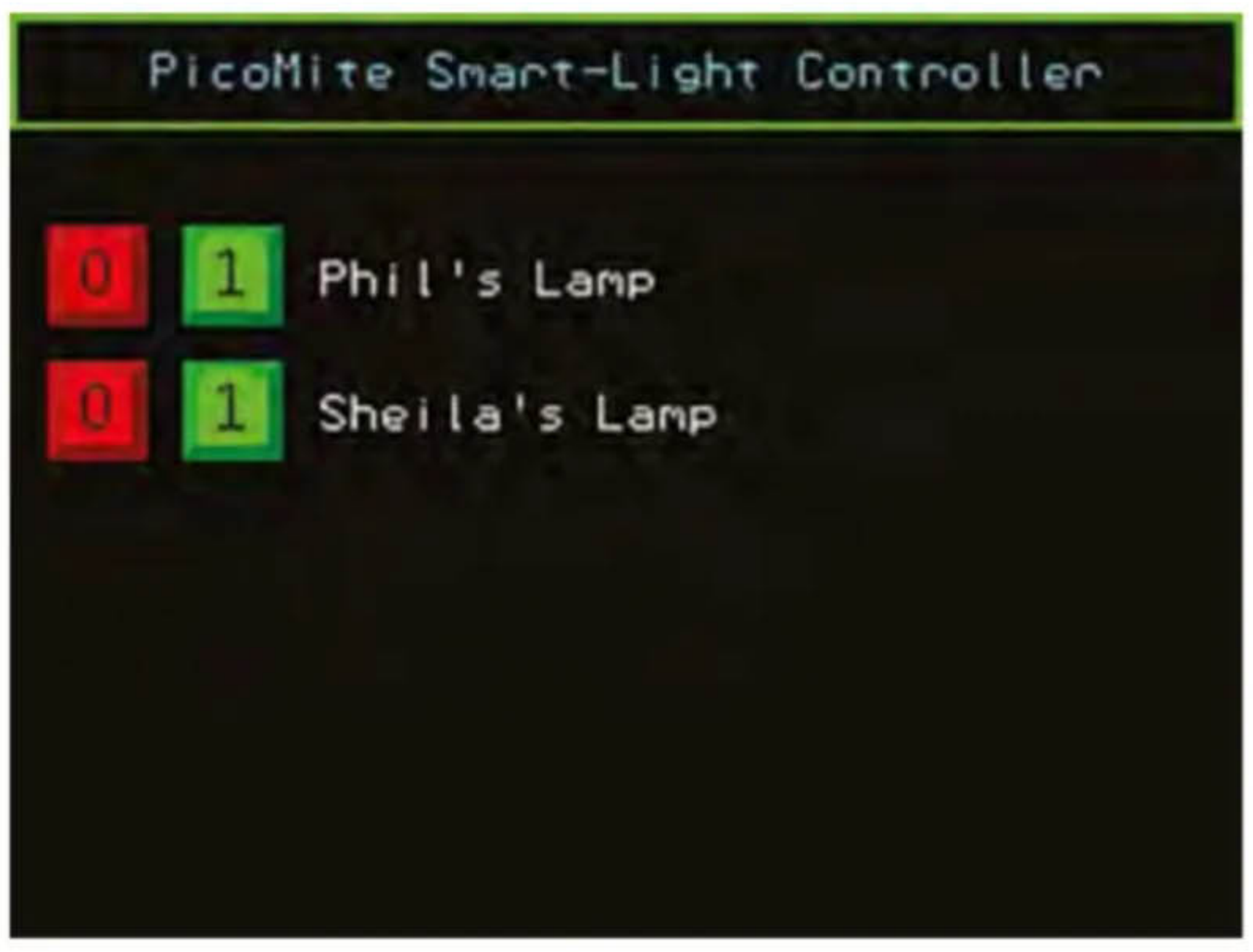
3. Select devices

- The tick box to the left of a device's name allows the adjacent device to toggle between selected, and unselected. When a device is selected, an 'X' will appear in the tick box (see Fig.6)
- The number of selected devices is displayed (in green) in the bottom-left corner of the screen, along with the total number of devices found.
- Once the required devices have been selected, the green 'Save' button is pressed. However, if no devices have been selected then pressing 'Save' will generate a warning message with an option to take the admin user back to the Select screen – see Fig.7.


PicoMite Smart-Light Controller

NO DEVICES SELECTED

Fig.7. If no smart devices are selected by the admin user, then this screen is displayed, with an option to jump back to the 'Select' screen.



PicoMite Smart-Light Controller

0 1 Phil's Lamp

0 1 Sheila's Lamp

Fig.8. The main user screen allows simple control of any listed smart device by pressing the relevant on (1) or off (0) button.

4. Refresh admin list (from Hub)

- The red 'Refresh' button in the bottom-right corner of the screen allows the admin user to refresh the list (displayed on the touchscreen) with all the devices that are configured in the Hue Hub. This is useful when new devices have been added to the Hue setup (via the Hue App), and which you subsequently want to be able to control from the *PicoMite Smart light Controller*.

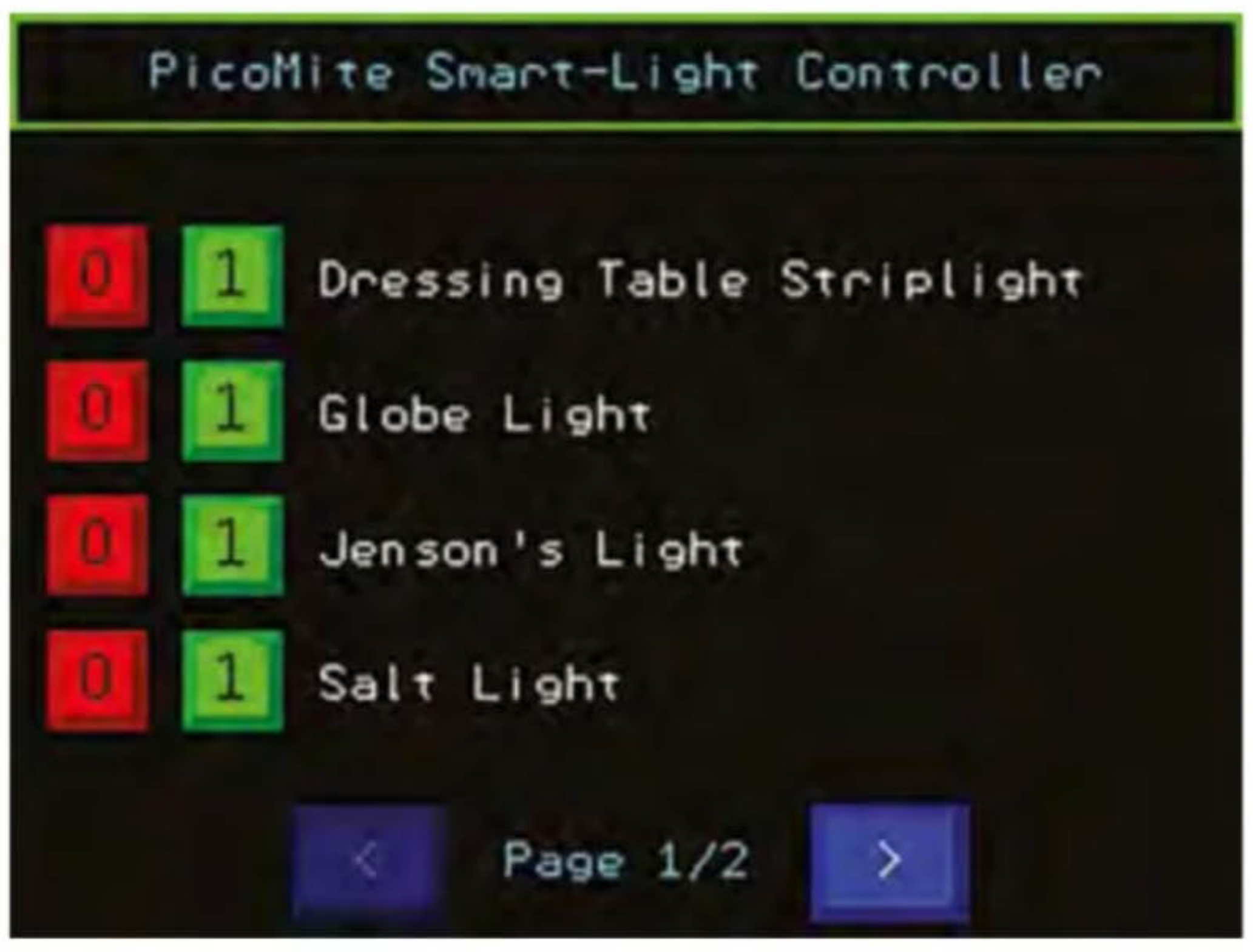
5. User list (selected devices)

- The user will only see a list of devices that they are able to control once a minimum of one device has been selected on the selection screen (and the 'Save' button pressed).
- If the user's list contains five devices or less, then they will be listed, as shown in Fig.8.
- If the user's list contains more than five devices, then multiple pages will be displayed (this time with the page navigator at the bottom of the screen) – see Fig.9.

6. Control device

- To the left of each named device is a red off button (marked '0') and a green on button (marked '1') – see Fig.8 and Fig.9. Pressing the appropriate button is all that is needed to control the relevant smart device.

The above six points are a summary of the process flow of the program code. By understanding these, along with looking at the comments in the MMBASIC program code, you should be able to follow how everything works.



PicoMite Smart-Light Controller

0 1 Dressing Table Striplight

0 1 Globe Light

0 1 Jenson's Light

0 1 Salt Light

< Page 1/2 >

Fig.9. When the user has access to more than five smart devices, a page navigator appears at the bottom of the screen.

Remember that the program code is there for you to add your own ideas. Let's discuss a few examples.

Possible upgrades

Once you start using the *PicoMite Smart light Controller*, you will no doubt think of many things that could be improved or added. Here are some ideas:

- Store the admin and user list of devices on either an SD card or in Flash memory (rather than having to perform the selection process each time you `RUN` the program)
- Distinguish between on/off-only devices and smart lights that are dimmable (for example, use different coloured names to distinguish between them)
- For dimmable smart lights, allow a percentage value (1-100) to be entered (or maybe create a sliding-bar graphic)
- Add password protection to access the admin list (accessed from the user list by tapping a secretly placed invisible touchscreen button)
- Have an admin menu to allow full configuration (eg, inputs for: Wi-Fi SSID, Wi-Fi Password, Hub IP address, Hub API)
  - Auto switch-off touchscreen after a period of non-use, and 'wake up' on touch
- Ability to rename a device via the touchscreen.

The above should provoke some ideas for you – and no doubt you can think of many more. Please do send me an email with a brief description of any custom version of the *PicoMite Smart light Controller* that you create – it is always great to hear from readers!

Next time

We have had several enquiries about whether there is a version of MMBASIC that will run on the wireless version of the Raspberry Pi Pico (rather than having to use an ESP32 Wi-Fi module connected to a standard Raspberry Pi Pico). The good news is that there is indeed a dedicated version of firmware available. So, next time we will discuss how to install MMBASIC onto a Raspberry Pi Pico W module; and we'll cover the many features and benefits it offers.

Until then, stay safe, and have FUN!

Questions? Please email Phil at:
contactus@micromite.org

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Max's Cool Beans

By Max the Magnificent

Arduino Bootcamp – Part 9

I know some cynical souls say nostalgia isn't what it used to be but – be that as it may – I must admit to feeling a tad nostalgic myself at the moment. Perhaps you would care to join me on a little trip down memory lane (cue audio and visual effects indicating a trip into the past).

Just a little nybble

Shake yourself down and take a few deep breaths. It will take only a couple of minutes to recover from the rush of racing through the timestream (it gets easier the more you do it, and you do it more the older you get).

It's generally accepted (although not undisputed) that the first commercial microprocessor was the Intel 4004, which was released into the world in 1971 when I was but 14 years of age. The 4004 was a 4-bit machine, which means it had a 4-bit data bus and it manipulated and stored data in 4-bit 'chunks' called 'nybbles'.

Comprising only around 2,300 transistors, the 4004 was a specialised device intended for use in electronic calculators. The next wave of microprocessors were predominantly 8-bit machines, which means they had 8-bit data buses and they manipulated and stored data in 8-bit 'bytes' (we introduced the concepts of bits, nybbles and bytes in *PE*, April 2023).

These 8-bit beauties included the Intel 8008 and 8080, which were introduced in 1972 and 1974, respectively. Other contenders from around that time were the 6800 from Motorola in 1974, the 6502 from MOS Technology in 1975, and the Z80 from Zilog in 1976 (to name but a few). Many of these appellations will stir fond memories in readers of a certain age.

Byte by byte

In an earlier column (*PE*, July 2023) we introduced the concept of the 'unsigned binary' format in which binary values can be used to represent only positive numbers. Also, we discussed the 'signed binary' format in which the same binary values can be used to represent both positive and negative numbers. As you may recall, a single 8-bit byte can embody $2^8 = 256$ patterns of 0s and 1s. In turn, these patterns can be used to represent unsigned integer values in the range 0 to 255 or signed integer values in the range –128 to +127.

Unfortunately, there's only so much one can do with a single byte. What if we wish to represent larger quantities? Well, the obvious solution is to use multiple bytes. For example, two bytes (16 bits) can embrace $2^{16} = 65{,}536$ patterns of 0s and 1s, which can be used to represent unsigned integers in the range 0 to 65,535 or signed integers in the range –35,658 to +35,657. Similarly, four bytes (32 bits) can encompass $2^{32} = 4{,}294{,}967{,}296$ patterns of 0s and 1s, which can be used to represent unsigned integers in the range 0 to 4,294,967,295 or signed integers in the range –2,147,483,648 to +2,147,483,647.

Do you speak $^&*_?

In the very early days of microprocessors, it was common to enter one's programs in machine code, which refers to the numerical values executed by the processor. One of the first single-board computers (SBCs) I recall seeing was in an advert here in *Practical Electronics* sometime around 1977. I drooled with desire when I cast my orbs on this little beauty, but I was an impoverished student at university at that time, so I didn't have two pennies to rub together, as they say.

In addition to its 8-bit processor chip, this board had a 4x4 keypad to enter instructions and data, some 7-segment displays (like the ones we're using in our *Arduino Bootcamp* series) so you could see what you were entering and view the results when your program stopped executing, and a couple of pushbuttons to set the program running or single-step through the code. It also had 1KB (one kilobyte) of random-access memory (RAM) and 2KB of pre-programmed read-only memory (ROM), where each KB is $1 \times 2^{10} = 1{,}024$ bytes.

RAM is volatile, which means it forgets its contents when power is removed from the system. By comparison, ROM is non-volatile, which means it retains its contents when the system is powered down. The RAM was used to store one's programs and data, while the ROM contained a monitor program that acted as the interface between the user and machine, watching the switches, driving the displays, and handing control over to the user's program when instructed to do so.

The next step up the programming ladder was to use a low-level language called 'assembly' in which each instruction is represented by a mnemonic (eg, `LDA $FF`, meaning 'load the accumulator register with the hexadecimal value FF'). At first, it was common to capture a program in assembly language using pencil and paper, to assemble (translate) that program into its corresponding machine code instructions by hand, and to enter the machine code into the computer using toggle switches and pushbuttons, simple keypads, or similar. As computers grew to have more memory and better interfaces like keyboards and screens, editor and assembler applications were employed to capture and assemble these programs.

Irrespective of whether you were working in machine code or assembly language, if you wanted to use multiple bytes to represent larger values, you were obliged to do everything by hand, which was time consuming and prone to error. Just to make things trickier, each microprocessor had its own instruction set and operation codes, its own assembly language and mnemonics, and its own way of doing things. Oh, the fun we had!

Next on the scene came higher-level programming languages like BASIC, which stands for 'Beginners' All-purpose Symbolic Instruction Code.' BASIC was originally developed at Dartmouth College in the early 1960s for use on 'big iron' (mainframe) computers. However, in 1975, Bill Gates and Paul Allen created a version that would run on one of the early microprocessor-based personal computers called the Altair (this was the start of the Microsoft Corporation we know and love to this day).

The great thing about using a higher-level language like Microsoft BASIC was that you could write your programs using large values (32-bit signed integers were the default) while leaving the BASIC interpreter to break things up into the 8-bit 'chunks' to be manipulated by the microprocessor.

How big, you ask?

This is probably a good time to remind ourselves that, in the case of the Arduino Uno we've been using in our experiments, we've been employing its integrated development environment (IDE) to enter our programs in a mixture of the C/C++ programming languages. Thus far, the way we've declared integer variables is to use the `int` data type, which – by default – instantiates a signed integer. If we wish to create an unsigned integer, we use `unsigned int`. As we discussed in one of my *Cunning Coding Tips and Tricks* columns (*PE*, September 2020), there are three different sizes of `int`. In addition to the regulator `int`, we also have `short int` and `long int` types.

The best way to wrap our brains around how we use these types to declare variables is illustrated below, where the red/bold parts are mandatory and the green parts are optional:

```
signed         int Fred;
unsigned       int Wilma;

signed   short int Barney;
unsigned short int Betty;

signed   long  int George;
unsigned long  int Jane;
```

This may seem confusing at first, but it does make sense. If we don't use the `signed` or `unsigned` keywords, the C/C++ compiler will assume `signed`. Similarly, if we use the keywords `short` or `long`, the compiler will assume we are using these to qualify an `int`, even if we neglect to explicitly say so. Where things get a little tricky is that the size of an `int`, a `short int`, and a `long int` vary from computer to computer. This is largely a function of the computer's internal architecture and data bus width. All we know for sure is that the C/C++ specifications state that the minimum size of a `short` is two bytes (16 bits), the minimum size of a `long` is four bytes (32 bits), and the size of a regular `int` is anybody's guess.

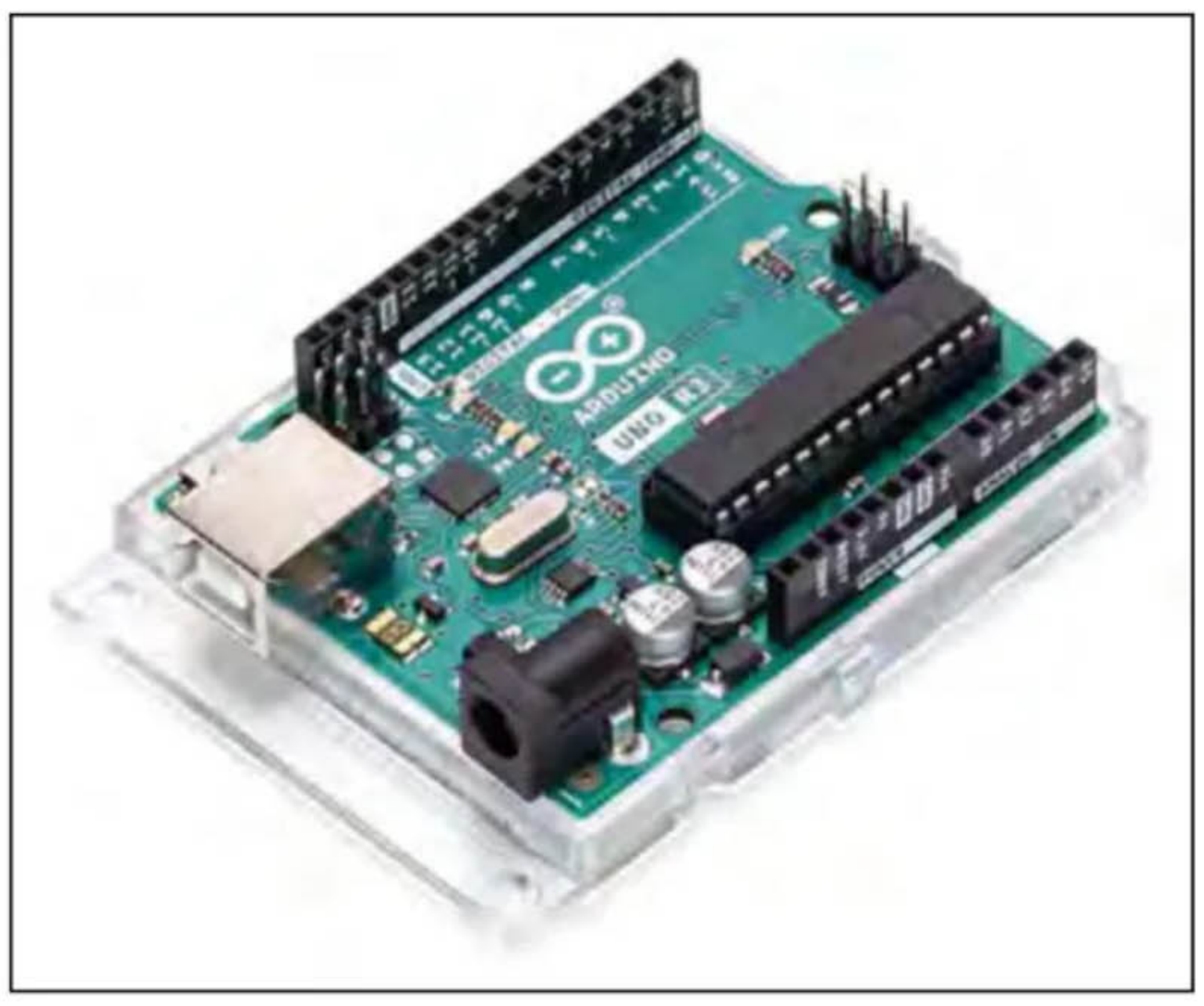


Fig.1. The Arduino Uno R3 microcontroller development board (the big 28-pin dual-inline (DIL) chip is the MCU (Source: Arduino)

In the case of an Arduino Uno R3 (the reason for the 'R3' qualifier will become apparent as we proceed), both an `int` and a `short` are two bytes, while a `long` is four bytes. Happily, the compiler understands what is required for different processors, which is why one of the first things we do is use the IDE to tell the compiler which development board we are working with.

Who's in control?

These days, microprocessors are often referred to as microprocessor units (MPUs). At the heart of an MPU is its central processing unit (CPU), which is where all the decision making and number crunching is performed. The principal elements of a CPU include a bunch of registers, an arithmetic-logic unit (ALU) that performs the arithmetic and logical operations, and a control unit that orchestrates the fetching (from memory), decoding, and execution of instructions, along with the storing (into memory) of results.

In the case of the early microprocessors that we are considering here, the terms MPU and CPU may be considered to be synonymous. By comparison, in addition to one or more CPU cores, today's MPUs also include things like on-chip cache memories, memory management units (MMUs), floating-point units (FPUs), and… the list goes on. One distinguishing characteristic of an MPU is that it requires additional components to realise a fully functioning computer system. These components include memory devices, interface devices, input/output (I/O) devices, and so forth.

By comparison, in addition to its CPU, a microcontroller unit (MCU) also contains on-chip memory (RAM, and ROM) along with other functions like counters, timers, pulse-width modulators (PWMs), analogue-to-digital converters (ADCs), and – once again – the list goes on. As a result, an MCU is essentially a small, fully functioning computer implemented on a single silicon chip.

The tried-and-true Uno R3

The first Arduino Uno (known as the R1 for 'Revision 1') was introduced in 2010. Following a couple of minor tweaks, the R3 appeared in 2011, and this is the version we've been using ever since. Indeed, it's the Uno R3 that has been powering the experiments throughout our *Arduino Bootcamp* (Fig.1).

The processor chip employed by Arduino Unos R1, R2 and R3 is an 8-bit MCU in the form of an ATmega328P. This was created by a company called Atmel, which was acquired by Microchip Technology in 2016. Running with a clock frequency of 16MHz, this MCU boasts 2KB of RAM and 32KB of Flash memory. The RAM is used to store variables and data, the Flash (sort of equivalent to ROM) is used to store the user's program. When the MCU is powered up, it immediately starts to execute whatever program is currently stored in its Flash memory.

Now, you may be thinking to yourself that 2KB of RAM and 32KB of Flash memory are not tremendously large amounts in the scheme of things, and you would not be incorrect. On the other hand, consider the latest-and-greatest dice rolling program that we created in our previous column (*PE*, August 2023). This program (a.k.a. 'sketch') waits for the user to press a button, which triggers it to generate a series of sixteen random values. The program presents these values on our 7-segment display, gradually slowing down until it settles on the final value. If you load this program into your Arduino's IDE and compile it, you'll see that it uses only 71 bytes (3%) of our RAM and 2012 bytes (6%) of our Flash memory. The bottom line is that you can get a lot done with only 2KB of RAM and 32KB of Flash.

You can refresh your (biological) memory by downloading, perusing, and pondering this code (file **CB-Sep23-01.txt**). As usual, all of the files mentioned in this column are available from the September 2023 page of the *PE* website at: **https://bit.ly/pe-downloads**

In addition to the processor itself, the Arduino Uno's printed circuit board (PCB) includes several other devices and connectors, which is why we refer to the whole ensemble as being a 'microcontroller development board.'

The Arduino Uno can be powered via its USB-B connector or via its 2.1mm power jack. In the latter case, a 7 to 12V power supply is recommended (you can go as high as 20V, but the regulator on the development board will run hot).

In addition to powering the Arduino, the USB-B connector can also be used to communicate control information and data between the Arduino and the host computer (*PE*, May 2023).

Bake your own R3

Thus far, all the experiments in our *Arduino Bootcamp* series have been based on the use of a breadboard. The advantage of this is that we haven't been obliged to solder anything.

Don't worry, we are going to stick with using our breadboard. Having said

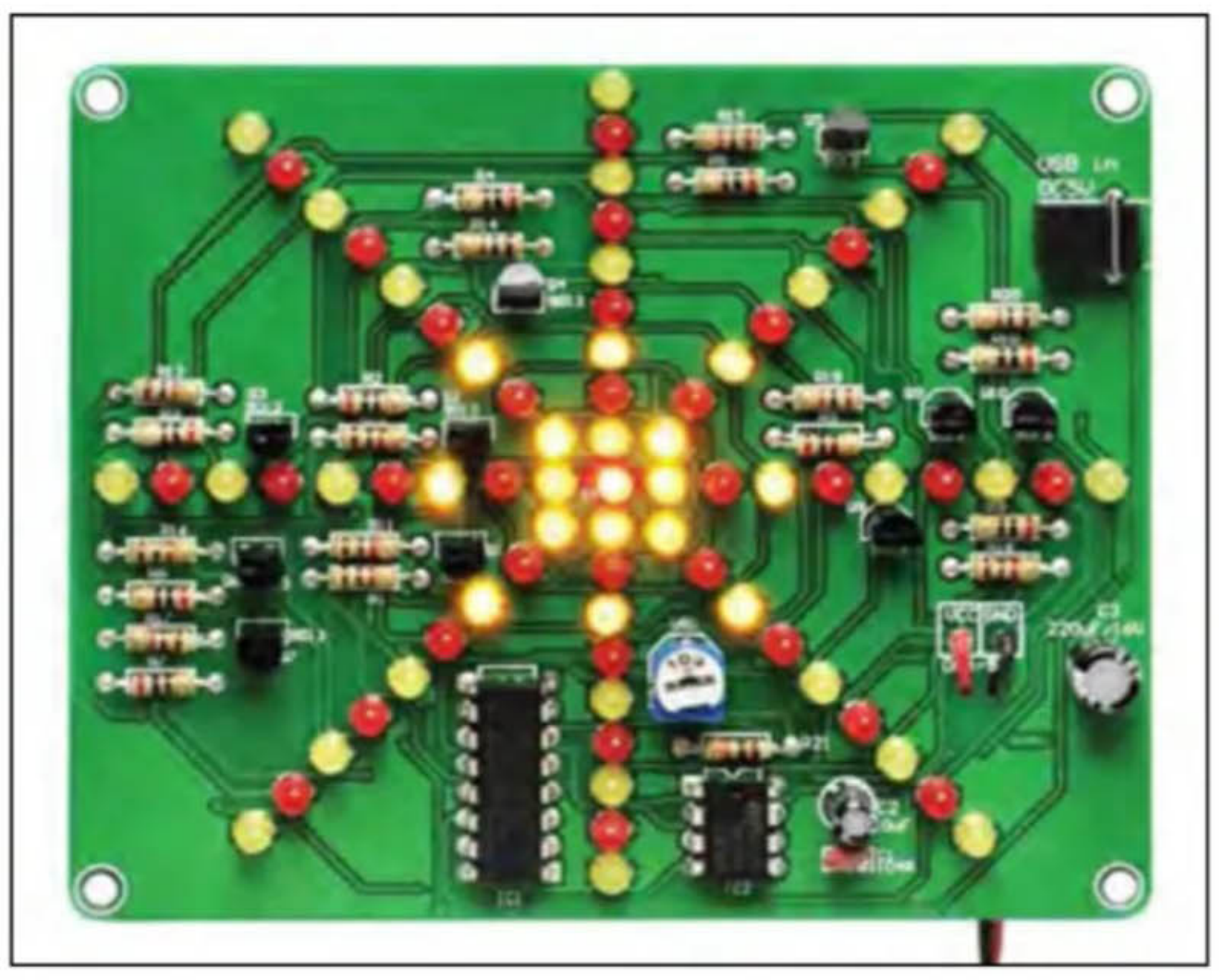


Fig.2. A handy and fun soldering practice board (Source: Gikfun)

this, the ability to solder opens a lot of doors when it comes to creating more involved projects. I taught myself how to solder when I was about 12 years old, which goes a long way to explain why so few of my early projects worked. If you are interested in learning to solder yourself, there are lots of cheap-and-cheerful tools available, like the Tabiger 60W Soldering Iron Kit for only £14.99 from Amazon: **https://bit.ly/43gtIV2**

I'd also recommend getting something like a Gikfun Soldering Practice Board (Fig.2) for only £11.98 from Amazon: **https://bit.ly/44gk1ay**

The advantages of practising with something like this are: (a) it's hard to mess things up, and (b) you end up with a bunch of flashing light-emitting diodes (LEDs). As I always say, show me a LED flashing and I'll show you a man drooling.

Just to add a big dollop of allegorical whipped cream on top of our metaphorical cake, a few years ago, *PE's* very own Alan Winstanley created an awesome *Basic Soldering Guide Handbook* – a 'must read' for beginners. If this book had been available to me when I was starting out, I would have saved myself from much gnashing of teeth and rending of garb, let me tell you. It's available for £11.49 from Amazon: **https://bit.ly/46CATKa**

The reason I'm waffling on about learning how to solder is that the nice folks at Arduino just gifted me with an Arduino *Make Your Own Uno Kit*. The whole point about this kit is that you get to solder all of the components yourself. The kit is available from the Arduino store for €41.25, see: **https://bit.ly/3PKd115**

I made mention of this little scamp earlier in this series, at which time I noted that it would be fun for all of us to be performing our experiments on Uno R3s that we had built ourselves. What I hadn't realised is that this kit comes with a second board – a 'shield' that plugs into the Arduino Uno – which acts as a music synthesiser (Fig.3).

The concept of plug-in shields has played a large part in the Uno's outstanding success (the folks at Arduino say 10 million Uno boards have shipped to date). The open-source nature of Arduino has allowed third-party vendors (both companies and individuals) to create shields carrying sensors, actuators, and displays, along with motor control shields, servo control shields, relay shields, Wi-Fi shields… the mind boggles.

I think it's safe to say that the footprint of the headers on the Arduino Uno has grown to be iconic. So-much-so, in fact, that it's not uncommon to see similar header arrangements on other microcontroller and field-programmable gate array (FPGA) development boards, because this allows those boards to take advantage of the Arduino's shield ecosystem.

Those were the days my friends…

I spent my formative years in the days of 8-bit processors, which is one of the reasons I'm so comfortable playing with the Uno R3. I also like the challenge of creating prodigious projects and implementing awesome algorithms while working under the limitations of the Uno R3's 8-bit data bus, 16MHz clock, 2KB of RAM, and 32KB or Flash memory.

I'm not alone in this. Back in the day, computer magazines used to run competitions to see who could implement a simple task – like counting the number of 1s in a byte or reversing the order of 0s and 1s from the least-significant bit (LSB) to the most-significant bit (MSB) – using the fewest number of memory locations or the least number of clock cycles. If you ever find yourself delving deeper into the nitty-gritty details of low-level programming, may I recommend *The Hacker's Delight* by Henry Warren, see: **https://bit.ly/3rwwdFs**

Having praised the Uno R3, it must be acknowledged that some projects require a bit more get-up-and-go on the processor front. There are, of course, a huge variety of Arduino boards, many with wider data buses, more memory, and higher clock speeds. Unfortunately, these boards fall short of the mark if you wish to keep on using all of the Uno shields in which you've invested your hard-earned moolah. In addition to the fact that they don't offer the Uno's header footprint, their digital I/O pins switch between 0V and 3.3V (the Uno R3's pins switch between 0V and 5V, which are – therefore – the values expected by Uno shields).

What we need is a new Uno with a 32-bit data bus, a faster clock, and more memory while maintaining the same header footprint and using the same 5V signals as the Uno R3 so it can work with all the existing shields that are out roaming around the world, but where will we find such a bodacious beauty?

Ah ha! Awe-inspiring Uno R4s

I am the bearer of glad tidings because I have wonderful news to impart. The folks at Arduino have just released two shiny and spiffy new platforms called the Uno R4 Minima and the Uno R4 Wi-Fi (Fig.4).

Right from the get-go, these bodacious beauties have the same footprint and support the same 5V signaling as the Uno R3 (hurrah!). The next thing to note is that the old USB-B connector has been replaced with its more modern USB-C counterpart. If you want to know more about this connector, you may find *The A, B, C of USB for Beginners* column to be of interest: **https://bit.ly/3OdIHuy**

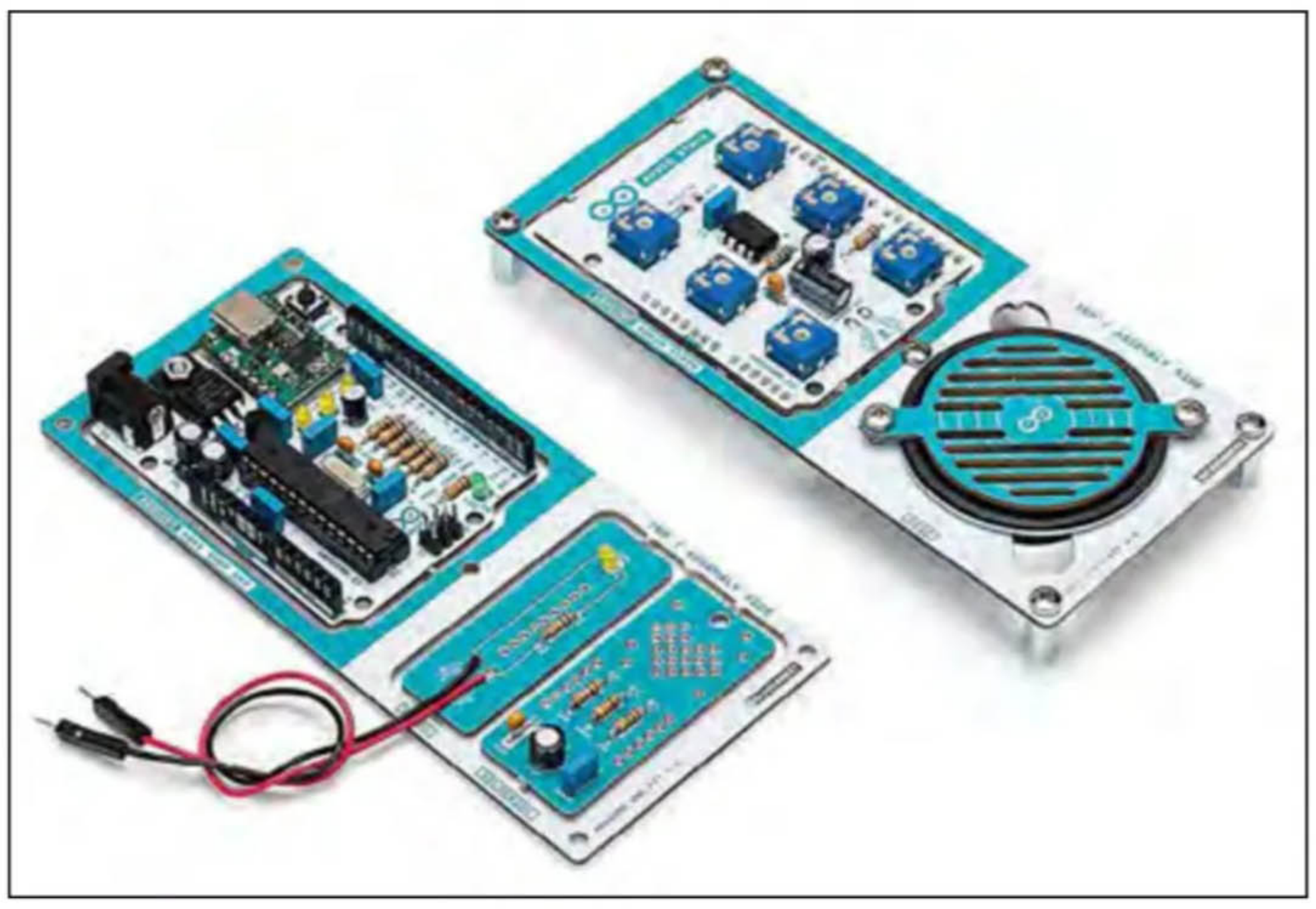


Fig.3. The assembled DIY Arduino Uno R3 (left) and music synthesiser shield (right) (Source: Arduino)

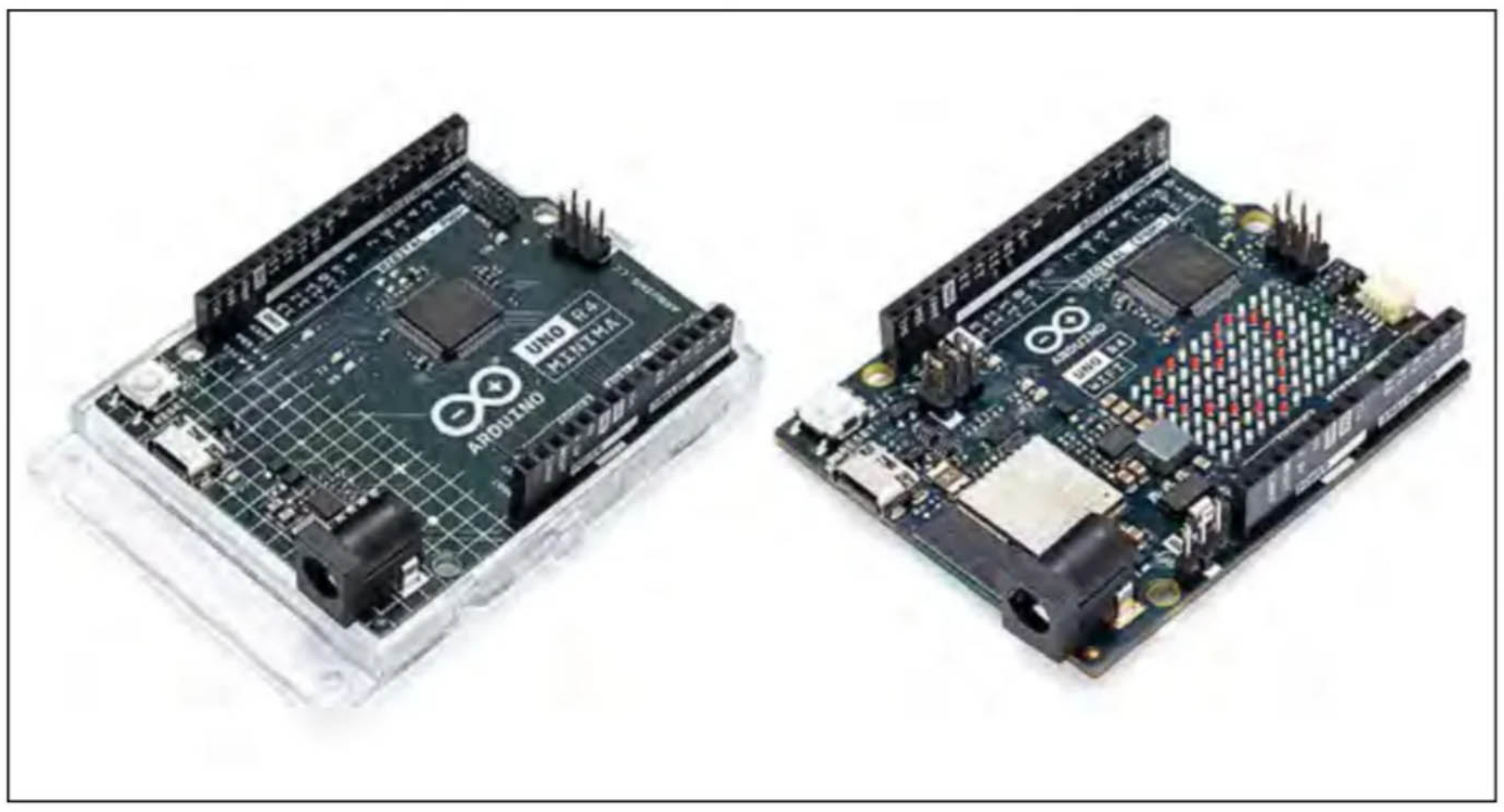


Fig.4. The Arduino Uno R4 Minima (left) and Arduino Uno R4 Wi-Fi (right) (Source: Arduino).

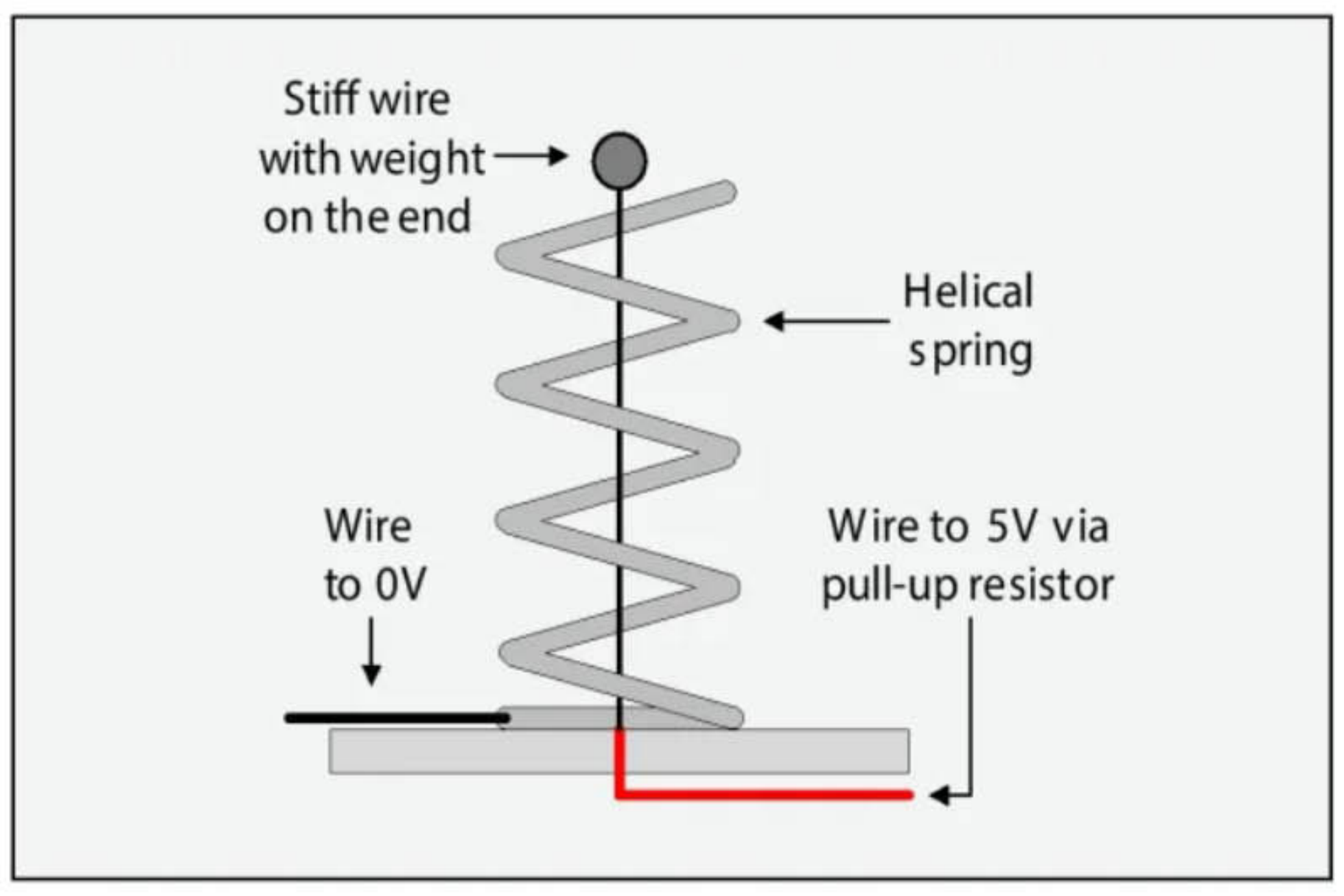

Stiff wire with weight on the end
Helical spring
Wire to 0V
Wire to 5V via pull-up resistor

Fig.5. DIY Trembler switch.

Also of interest is the fact that the maximum power supply voltage via the power jack has been increased to 24V with an improved thermal design.

Now let's turn our attention to the boards themselves, starting with the R4 Minima. Some Arduino users wish to communicate with devices using a Controller Area Network (CAN) bus. To do this with the Uno R3, users were obliged to use a CAN shield, so they will be happy to learn that the Uno R4 offers a CAN bus interface along with the existing UART, I^{2}C and SPI interfaces.

Of course, the part in which we are most interested is the Uno R4's processor, which is a RA4M1 microcontroller from Renesas. This device is based on a 32-bit Arm Cortex-M4F core, where the 'F' indicates the inclusion of a hardware floating-point unit (FPU).

The Uno R4's 32-bit data bus is four times the width of the Uno R3's 8-bit bus. As far as the compiler is concerned, integers of type `short` and `long` are still 16 bits (2 bytes) and 32 bits (4 bytes) wide, respectively. However, the size of a regular `int` with an R4 is now 32 bits, as opposed to only 16 bits in an R3. There are all sorts of interesting implications to this, but nothing that would affect anything we've been doing, so we'll leave those discussions to a future column.

The R4's clock runs at 48MHz (three times the R3), it's equipped with 32KB of SRAM (16 times the R3), and it boasts 256KB of Flash memory (8 times the R3). I ask you… what's not to love?

Now let's turn our attention to the Uno R4 Wi-Fi, which is based on the same microcontroller as the R4 Minima. However, the R4 Wi-Fi also sports an Espressif ESP32-S3 module for Wi-Fi and Bluetooth Low Energy connectivity. As we see in Fig.4, this little ragamuffin also flaunts a super-bright 12x8 red LED matrix, which can be used for things like displaying animations reflecting the values of sensor data without the need for any additional hardware.

Using the R4 Uno Wi-Fi, we can do things like connect to the Arduino Cloud. In turn, this allows is to do things like create web-based dashboards packed with customisable widgets, with which we can visualise historical or real-time data in the cyberworld and control things in the real world. Once again, however, we will leave further discussions on this topic for a future time because we currently have other fish to fry.

I'm all atremble

We seem to have wandered off into the weeds. Why didn't you stop me from waffling on so much? At the end of last month's column (*PE*, August 2023) I suggested we might add a 'nudge nudge' feature to the latest and greatest version of our dice rolling program. I also noted that, to do this, we could build a DIY 'trembler switch' (these are officially called 'vibration switches') as illustrated in Fig.5.

We can think of this implementation as being 'A poor person's accelerometer/motion sensor.' The idea is that a sufficient shock, like banging the table, will cause the weighted wire to move and complete the electrical circuit. Once our program is displaying its final value, if our trembler switch is triggered ('nudged') anytime during the `PAUSE_AFTER_ROLL` delay, then we could perform an additional random roll of our dice.

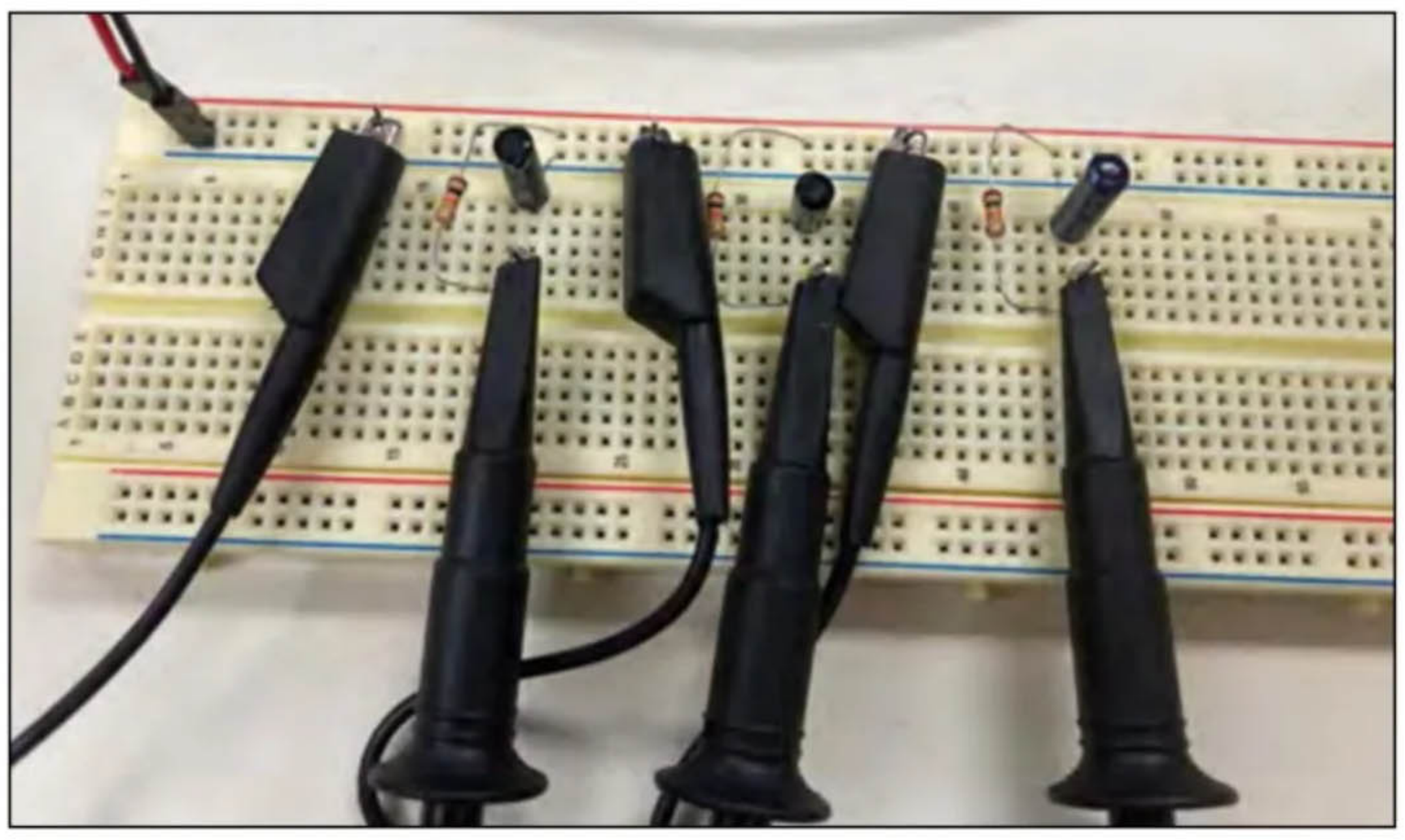


Fig.6. Testing my vibration ('trembler') switches.

Did you build one of these? I was going to, but I got distracted by… SQUIRREL! So, I ended up purchasing an off-the-shelf device. Actually, I acquired three different types from The PiHut (**thepihut.com**):

- Slow/hard-to-trigger version: **https://bit.ly/3rBOgdm**
- Medium type: **https://bit.ly/3pPiadP**
- High-sensitivity/easy-to-trigger implementation: **https://bit.ly/46SfDA4**

You can also source these slow (SW-18030P), medium (SW-18020P), and fast (SW-18010P) devices from suppliers like Adafruit and eBay.

The first thing I did when these little rascals arrived was to mount them on a breadboard. Each had one side connected to 0V and the other side connected to 5V via a 10kΩ pull-up resistor (Fig.6).

I connected three oscilloscope probes to the tap (measurement) points between each switch and its associated pull-up resistor, and then devoted a few happy minutes to banging the table to see what happened. It didn't take long to decide that, for this application, the most sensitive, fast-acting switch was the one for me.

I drooled with delight at the trace from this device (Fig.7). In this case, the horizontal timebase is set to 50 microseconds (µS) per division, which means the vibration continues for approximately 300µS, which is 0.3 milliseconds (ms).

Armed with this newfound knowledge, I added my trembler switch to the breadboard I've been using for our

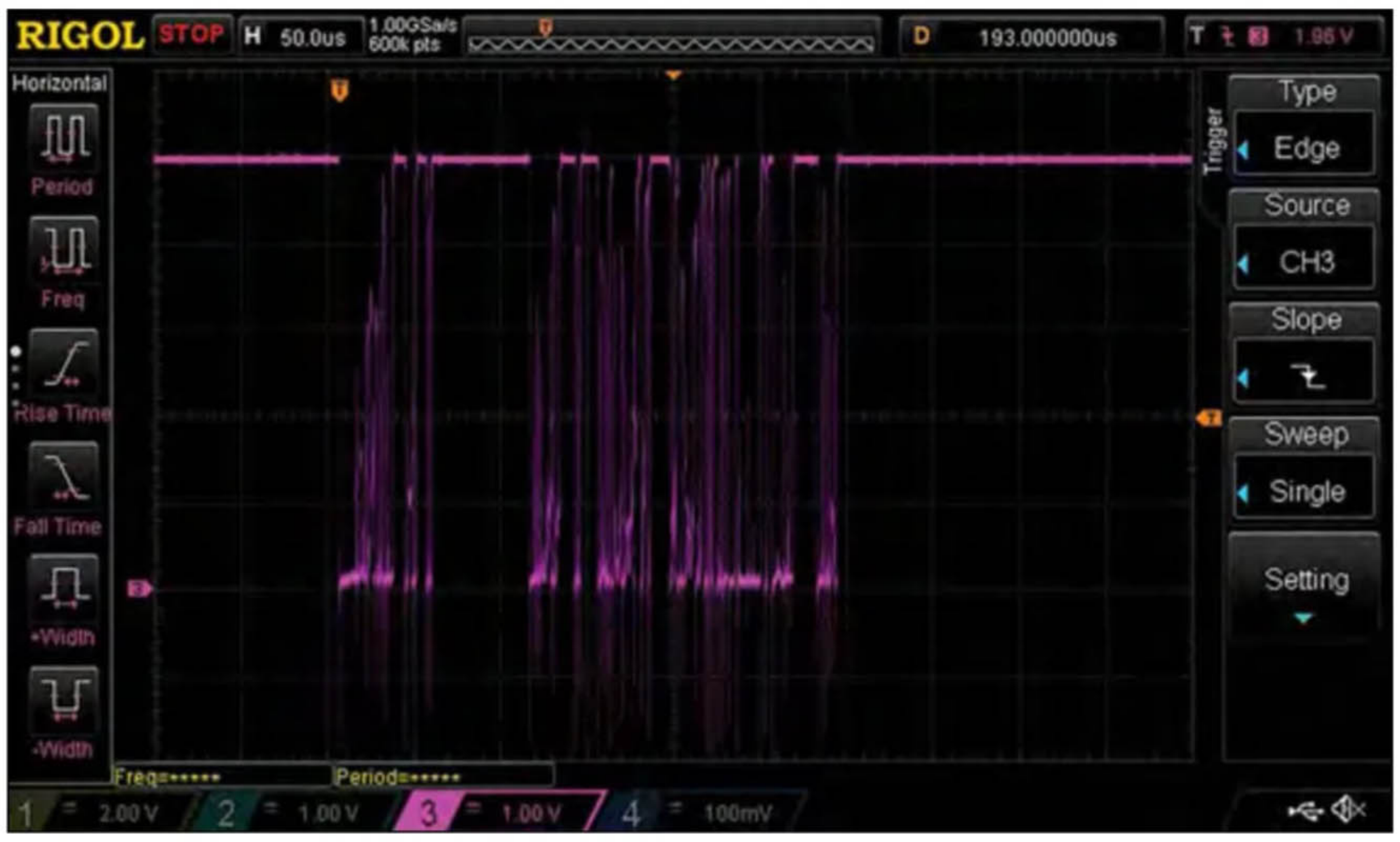


Fig.7. Example result from the sensitive vibration switch.

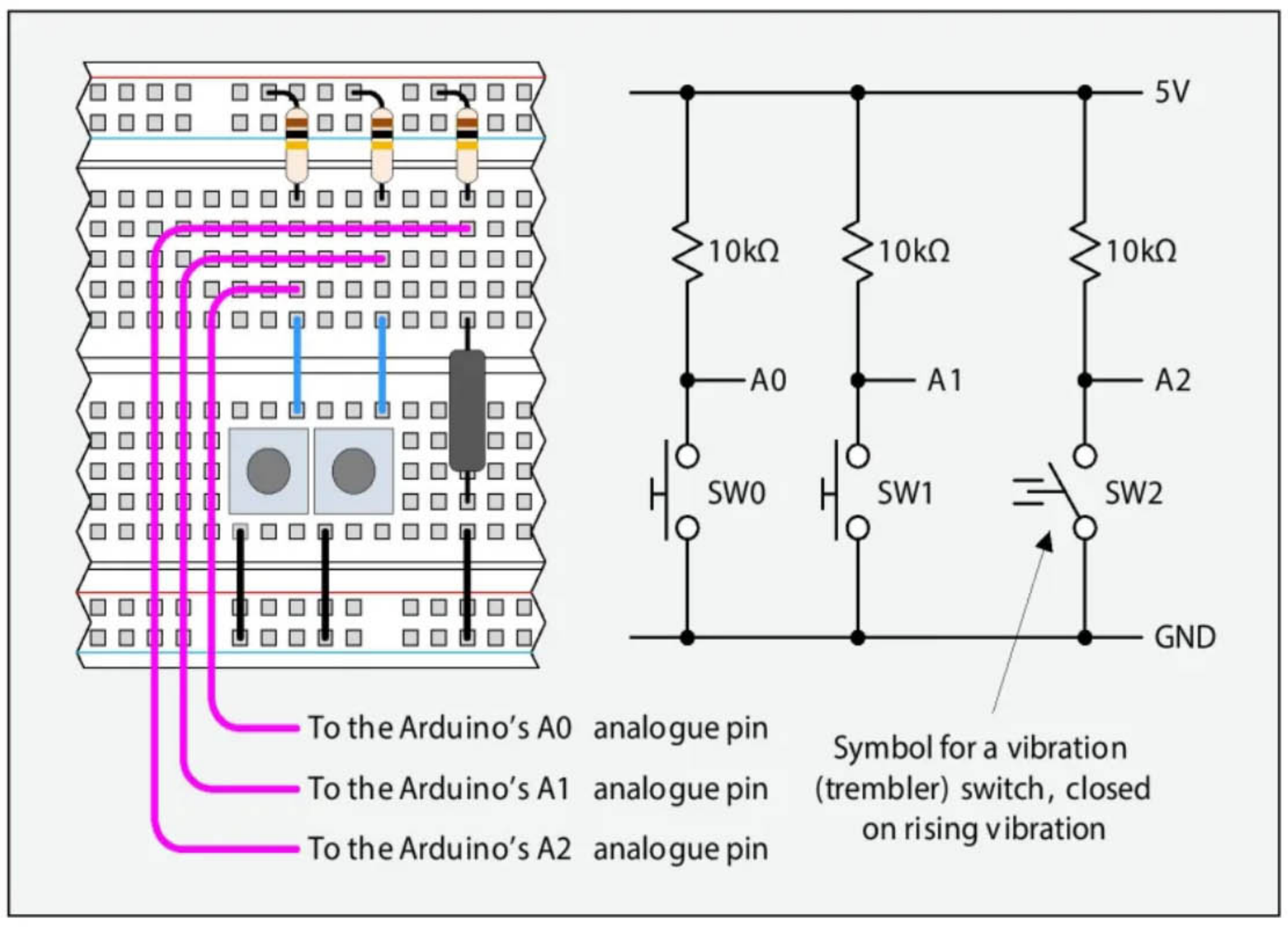
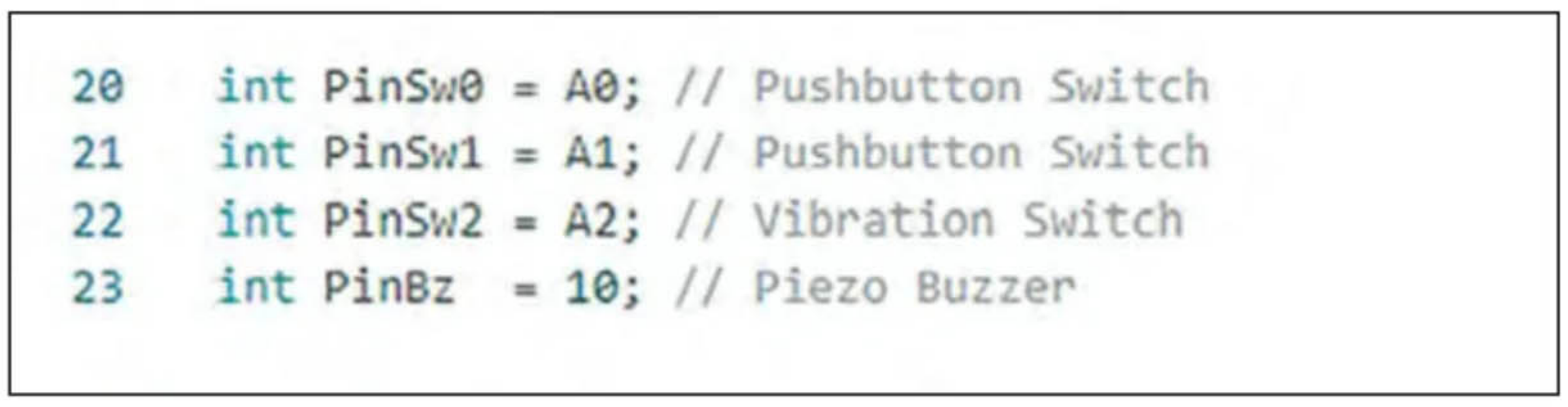
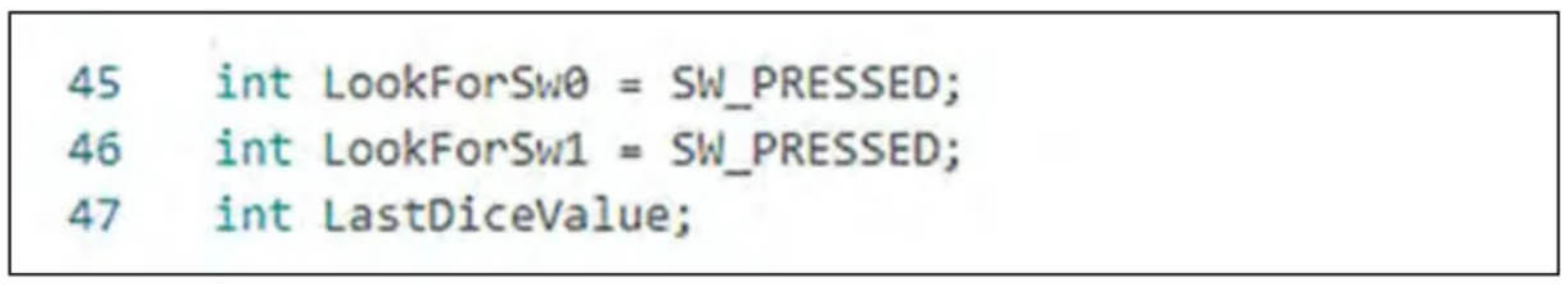

5V
10kΩ
10kΩ
10kΩ
A0
A1
A2
SW0
SW1
SW2
GND
To the Arduino's A0 analogue pin
To the Arduino's A1 analogue pin
To the Arduino's A2 analogue pin
Symbol for a vibration (trembler) switch, closed on rising vibration

Fig.8. Adding the vibration (trembler) switch to our breadboard.



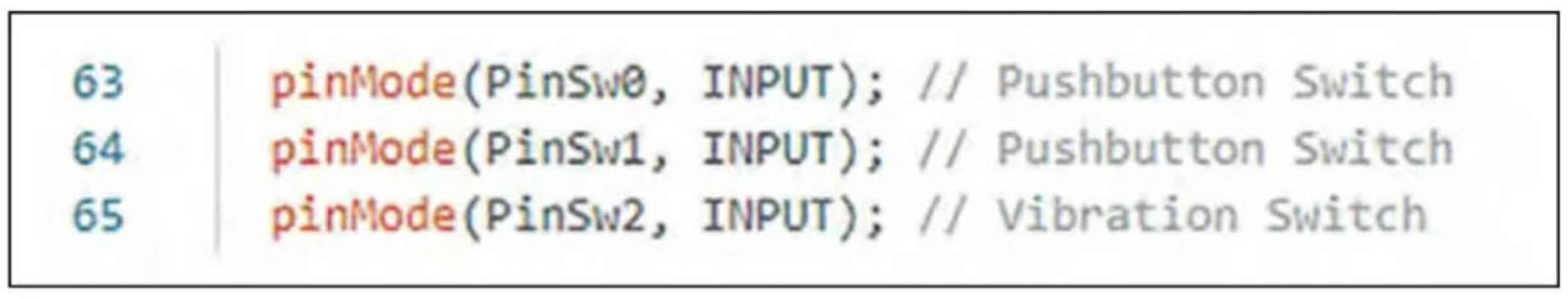
```
20   int PinSw0 = A0; // Pushbutton Switch
21   int PinSw1 = A1; // Pushbutton Switch
22   int PinSw2 = A2; // Vibration Switch
23   int PinBz  = 10; // Piezo Buzzer
```

Listing 1. Adding a new pin definition.



```
45   int LookForSw0 = SW_PRESSED;
46   int LookForSw1 = SW_PRESSED;
47   int LastDiceValue;
```

Listing 2. Adding a new global variable.



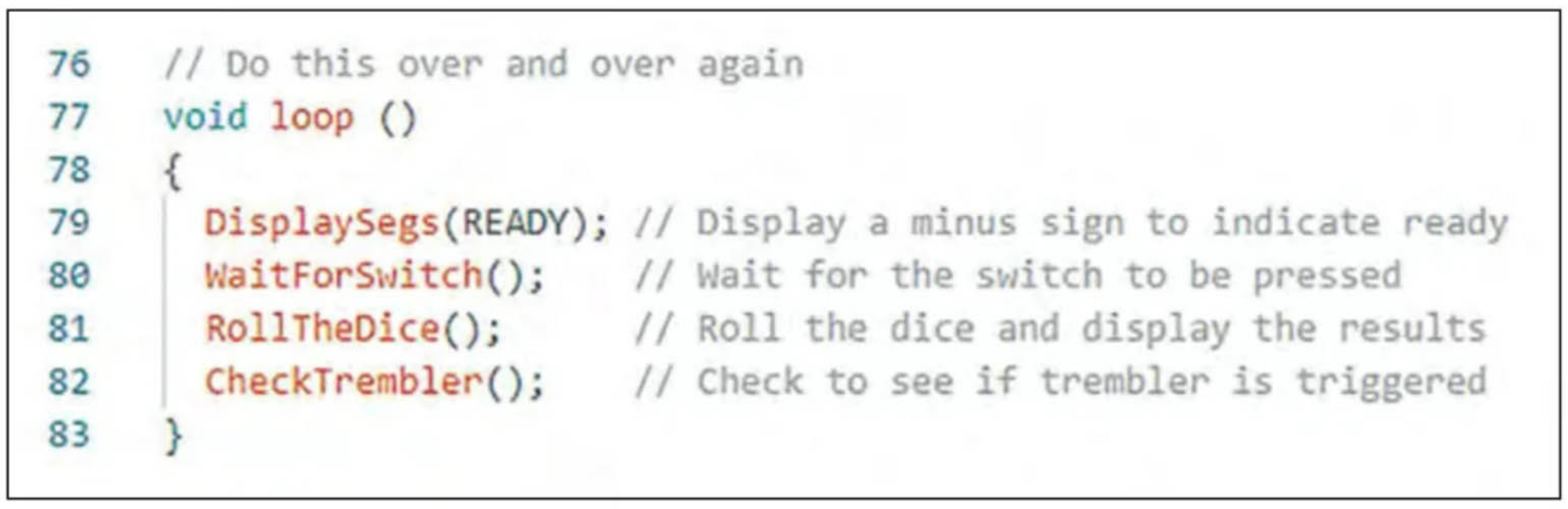
```
63     pinMode(PinSw0, INPUT); // Pushbutton Switch
64     pinMode(PinSw1, INPUT); // Pushbutton Switch
65     pinMode(PinSw2, INPUT); // Vibration Switch
```

Listing 3. Modifying the `setup()` function.

Arduino Bootcamp experiments and connected its tap point to the Arduino's A2 analogue input (Fig.8). As usual, you can download an image of our current breadboard layout showing all three switches, our buzzer and our 7-segment display – along with various pull-up and current-limiting resistors – coupled with the connections to our Arduino Uno – see file **CB-Sep23-02.pdf**

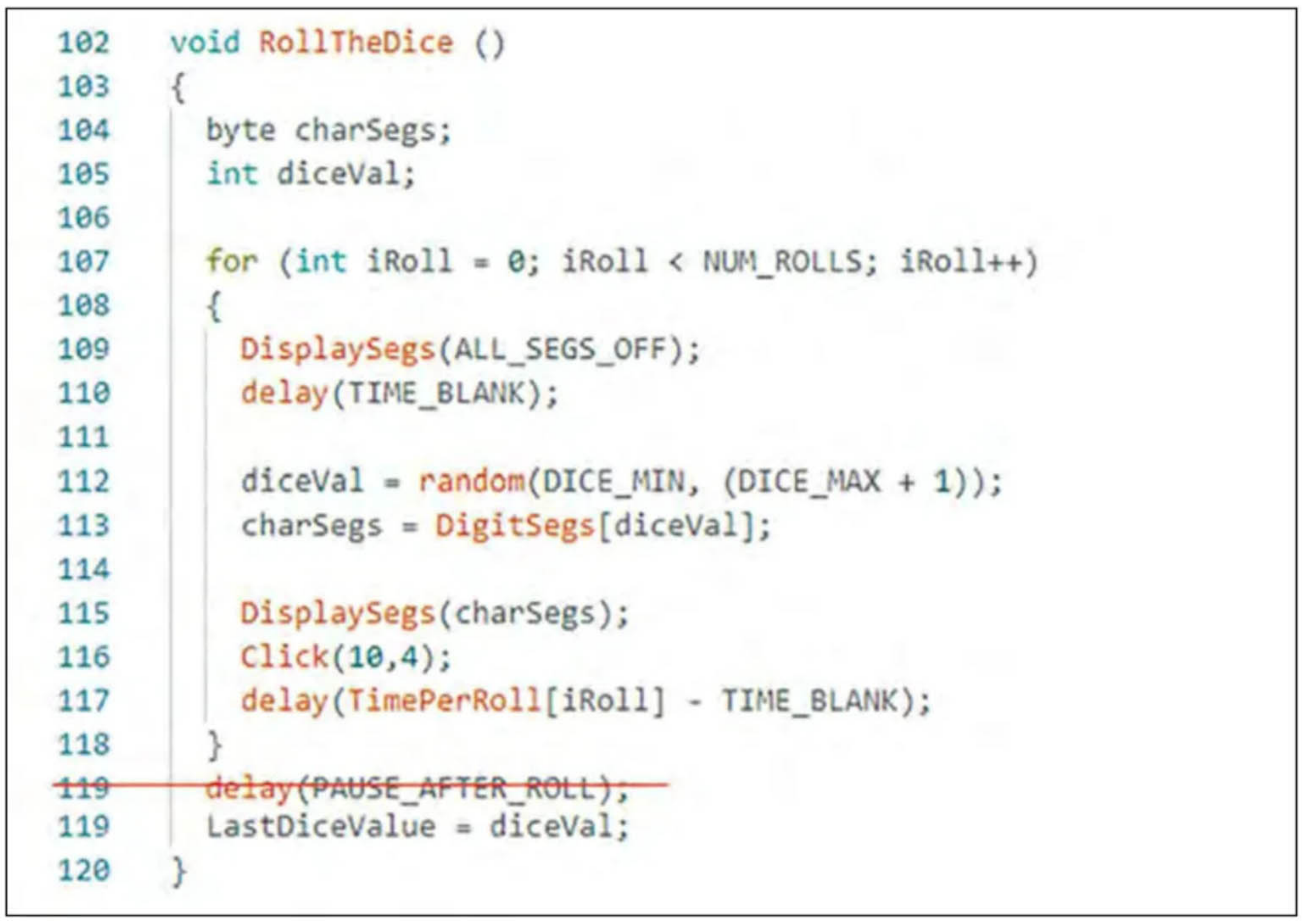
Tremble away!

To add our 'nudge nudge' feature, we will use our existing dice rolling program as a starting point (file **CB-Sep23-01.txt**). The first thing we are going to do is add a new pin definition on Line 22 for the pin that's connected to our vibration switch (Listing 1). (Note that any line numbers specified here relate to the new version of our program because the changes we are making will modify the existing code.)



```
76   // Do this over and over again
77   void loop ()
78   {
79     DisplaySegs(READY); // Display a minus sign to indicate ready
80     WaitForSwitch();    // Wait for the switch to be pressed
81     RollTheDice();      // Roll the dice and display the results
82     CheckTrembler();    // Check to see if trembler is triggered
83   }
```

Listing 4. Modifying the `loop()` function.



```
102   void RollTheDice ()
103   {
104     byte charSegs;
105     int diceVal;
106
107     for (int iRoll = 0; iRoll < NUM_ROLLS; iRoll++)
108     {
109       DisplaySegs(ALL_SEGS_OFF);
110       delay(TIME_BLANK);
111
112       diceVal = random(DICE_MIN, (DICE_MAX + 1));
113       charSegs = DigitSegs[diceVal];
114
115       DisplaySegs(charSegs);
116       Click(10,4);
117       delay(TimePerRoll[iRoll] - TIME_BLANK);
118     }
~~119     delay(PAUSE_AFTER_ROLL);~~
119     LastDiceValue = diceVal;
120   }
```

Listing 5. Modifying the `RollTheDice()` function.

Components from Part 1

LEDs (assorted colours)	https://amzn.to/3E7VAQE
Resistors (assorted values)	https://amzn.to/3O4RvBt
Solderless breadboard	https://amzn.to/3O2L3e8
Multicore jumper wires (male-male)	https://amzn.to/3O4hnxk

Components from Part 2

7-segment display(s)	https://amzn.to/3Afm8yu

Components from Part 5

Momentary pushbutton switches	https://amzn.to/3Tk7Q87

Components from Part 6

Passive piezoelectric buzzer	https://amzn.to/3KmxjcX

Components for Part 9

SW-18010P vibration switch	https://bit.ly/46SfDA4

Next, we are going to add a new global variable on Line 47 in the form of an `int` called `LastDiceValue` (Listing 2). We are going to use this value to keep track of the final value from the initial roll because – in this case – if we do trigger a tremble, we want the resulting dice value to be different to the old one.

In the case of our `setup()` function, all we need to do is add a new Line 65 in which we declare the pin connected to our vibration switch as being of type `INPUT` (Listing 3).

Our original `loop()` function contains three calls to functions whose names speak for themselves. After displaying our 'ready' symbol, waiting for the switch to be pressed, and rolling the dice, we are going to add a new call on Line 82 to a function that checks to see if the vibration switch has been triggered (Listing 4).

As you may recall, the last line of our existing `RollTheDice()` function caused the program to pause for our `PAUSE_AFTER_ROLL` delay, which is currently set to two seconds. We are going to delete this statement from Line 119 and replace it with a new statement that stores the final dice value in our global `LastDiceValue` variable, as illustrated in Listing 5.

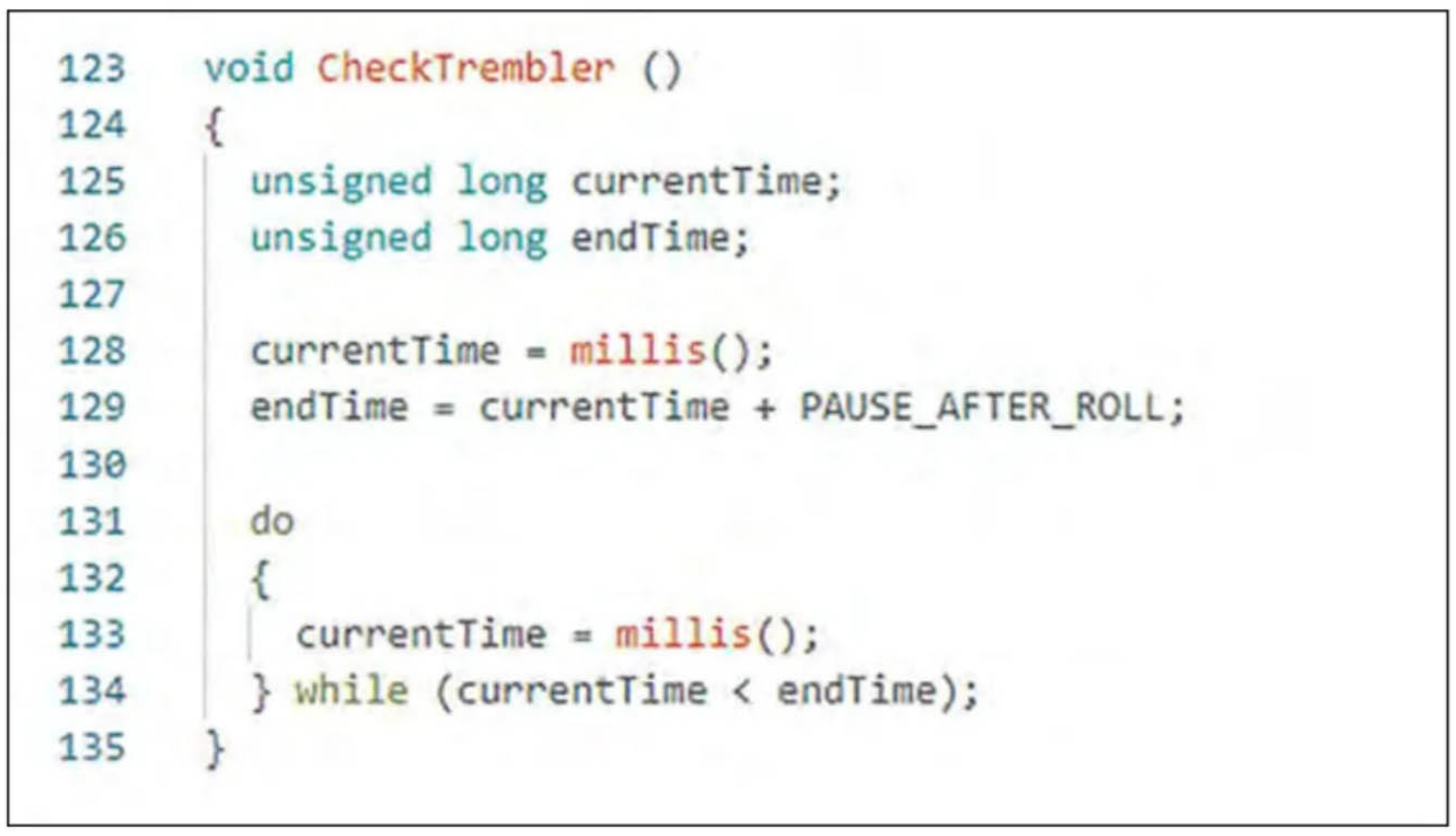
Next, we are going to take an initial stab at the `CheckTrembler()` function. The first thing we need to do is to re-implement the `PAUSE_AFTER_ROLL` delay in a new form, as shown in Listing 6.

Do you remember the `unsigned long` data type we discussed earlier? Well, on Lines 125 and 126 we start by declaring two local variables of this type called `currentTime` and `endTime` (this is uncanny – it's almost as if I had a plan).

On Line 128 we assign the value returned from the Arduino's in-built `millis()` function to our `currentTime` variable. This function returns the number of milliseconds passed since the Arduino board began running the current program (this number will overflow (return to zero), after approximately 50 days).

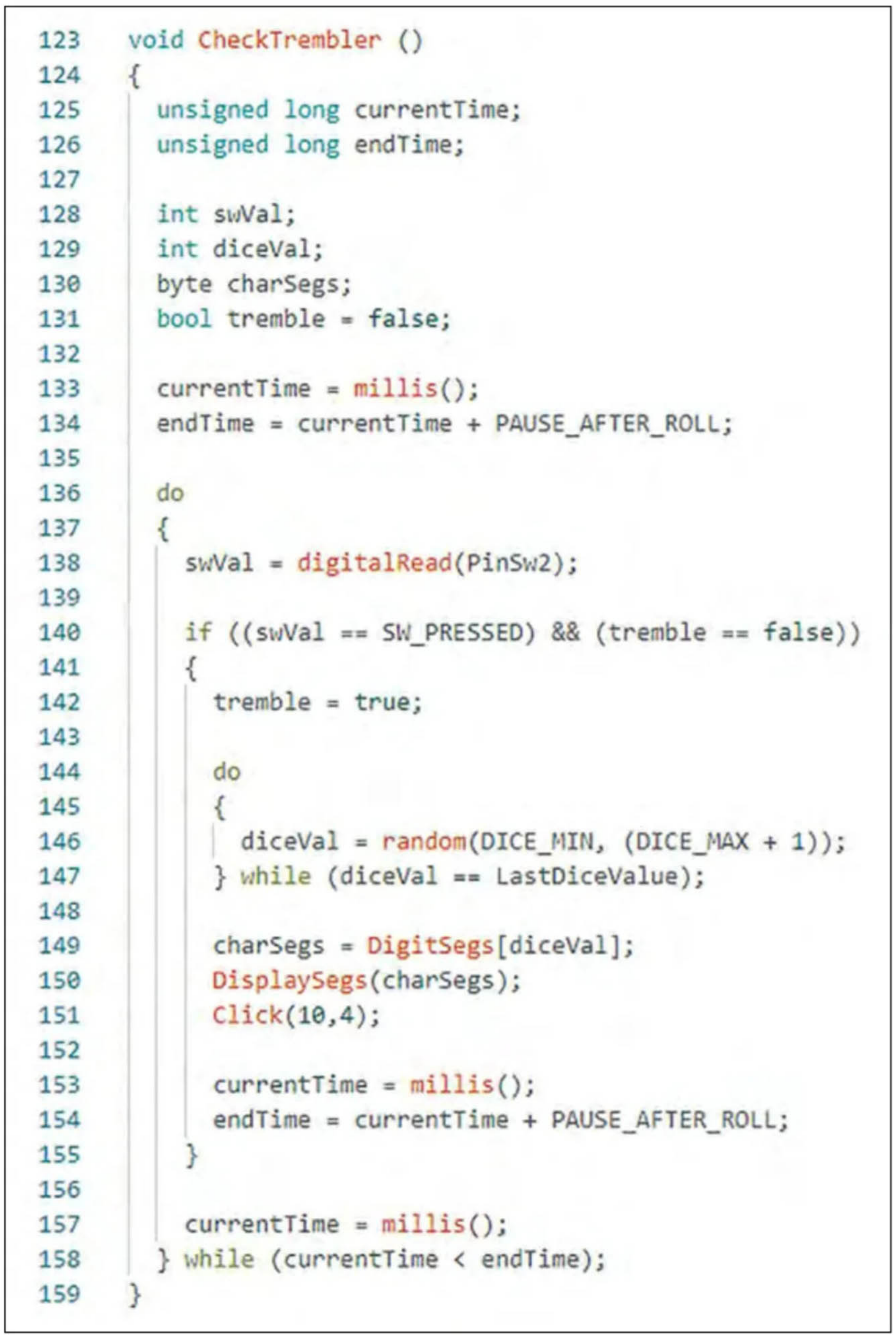
On Line 129 we assign the sum of the value stored in `currentTime` and our `PAUSE_AFTER_ROLL` delay to our `endTime` variable, which results in the time stored in `endTime` being 2000ms (two seconds) in the future.

Finally, in Lines 131 through 134, we enter a `do-while` loop (we introduced these constructs in *PE*, March 2023). At the moment, all we are doing is looping around loading our `currentTime` variable with the latest value



```
123  void CheckTrembler ()
124  {
125    unsigned long currentTime;
126    unsigned long endTime;
127
128    currentTime = millis();
129    endTime = currentTime + PAUSE_AFTER_ROLL;
130
131    do
132    {
133      currentTime = millis();
134    } while (currentTime < endTime);
135  }
```

Listing 6. First-pass `CheckTrembler()` function.



```
123  void CheckTrembler ()
124  {
125    unsigned long currentTime;
126    unsigned long endTime;
127
128    int swVal;
129    int diceVal;
130    byte charSegs;
131    bool tremble = false;
132
133    currentTime = millis();
134    endTime = currentTime + PAUSE_AFTER_ROLL;
135
136    do
137    {
138      swVal = digitalRead(PinSw2);
139
140      if ((swVal == SW_PRESSED) && (tremble == false))
141      {
142        tremble = true;
143
144        do
145        {
146          diceVal = random(DICE_MIN, (DICE_MAX + 1));
147        } while (diceVal == LastDiceValue);
148
149        charSegs = DigitSegs[diceVal];
150        DisplaySegs(charSegs);
151        Click(10,4);
152
153        currentTime = millis();
154        endTime = currentTime + PAUSE_AFTER_ROLL;
155      }
156
157      currentTime = millis();
158    } while (currentTime < endTime);
159  }
```

Listing 7. Fleshed-out `CheckTrembler()` function.

returned from the `millis()` function. The loop will terminate when the value in `currentTime` is equal to or greater than the value in `endTime`.

Feel free to peruse and ponder the current state of play (file **CB-Sep23-03.txt**). Of course, all we've done so far is to replicate the functionality we had in our original program. As we've discussed before, however, we can make our lives a lot easier by taking things one step at a time. Let's try compiling this to see if it works. It does. Hurray!

At this point we are ready to actually add the nitty-gritty tremble functionality to our `CheckTrembler()` function, as illustrated in Listing 7. In Line 128 we declare a `swVal` variable (we're going to use this like we did in our `WaitForSwitch()` function, except that this time we will be checking the state of our vibration switch).

In Lines 129 and 130 we declare `diceVal` and `charSegs` variables (we are going to use these like we did in our `RollTheDice()` function).

In line 131 we declare a Boolean variable of type `bool` called `tremble` to which we assign a value of `false` (which we take to mean that a vibration has not yet occurred). Last month, we said the user will be able to activate the vibration switch only a single time, and this is the variable we're going to use to make sure we stay true to our word.

Our original outer `do-while` loop starting on Line 136 and ending on Line 158 remains the same. Inside this loop, we first read the value from our vibration switch on Line 138. Next, on Line 140, we check to see if the switch has been activated (a 'nudge' from the user) while also checking that we haven't previously detected a vibration. If both these conditions are true, then the first thing we do on Line 142 is assign a value of `true` to our `tremble` variable, thereby ensuring that we won't respond to a future 'nudge.'

Lines 144 to 147 implement another `do-while` loop. In this case we keep on generating new random numbers as long as the new values are the same as the one that is currently on the display. We exit this loop as soon as our new random number is different to the old value.

We use Lines 149 to 151 to present our new ('nudged') value on the 7-segment display. Finally, on Lines 153 and 154 we reset things so that we will display our new value for the full `PAUSE_AFTER_ROLL` delay before returning control to the main `loop()` function.

All I can say is that this latest version of our code works like a charm (file **CB-Sep23-04.txt**). So, what are we going to do next? Well, one thing we could do is create a reaction tester to see how fast we can respond to changes on our display. Another possibility is to employ some different types of sensors (eg, light and temperature) to control our display. All will be revealed next month. Until then, have a good one!

Online resources

For the purposes of this series, I'm going to assume that you are already familiar with fundamental concepts like voltage, current and resistance. If not, you might want to start by perusing and pondering a short series of articles I penned on these very topics – see: **https://bit.ly/3EguiJh**

Similarly, I'll assume you are no stranger to solderless breadboards. Having said this, even if you've used these little scamps before, there are some aspects to them that can trap the unwary, so may I suggest you feast your orbs on a column I wrote just for you – see: **https://bit.ly/3NZ70uF**

Last, but not least, you will find a treasure trove of resources at the **Arduino.cc** website, including example programs and reference documentation.

Cool bean Max Maxfield (Hawaiian shirt, on the right) is emperor of all he surveys at **CliveMaxfield.com** – the go-to site for the latest and greatest in technological geekdom.

Comments or questions? Email Max at: **max@CliveMaxfield.com**

AUDIO OUT

By Jake Rothman

Discrete audio op amp – Part 1

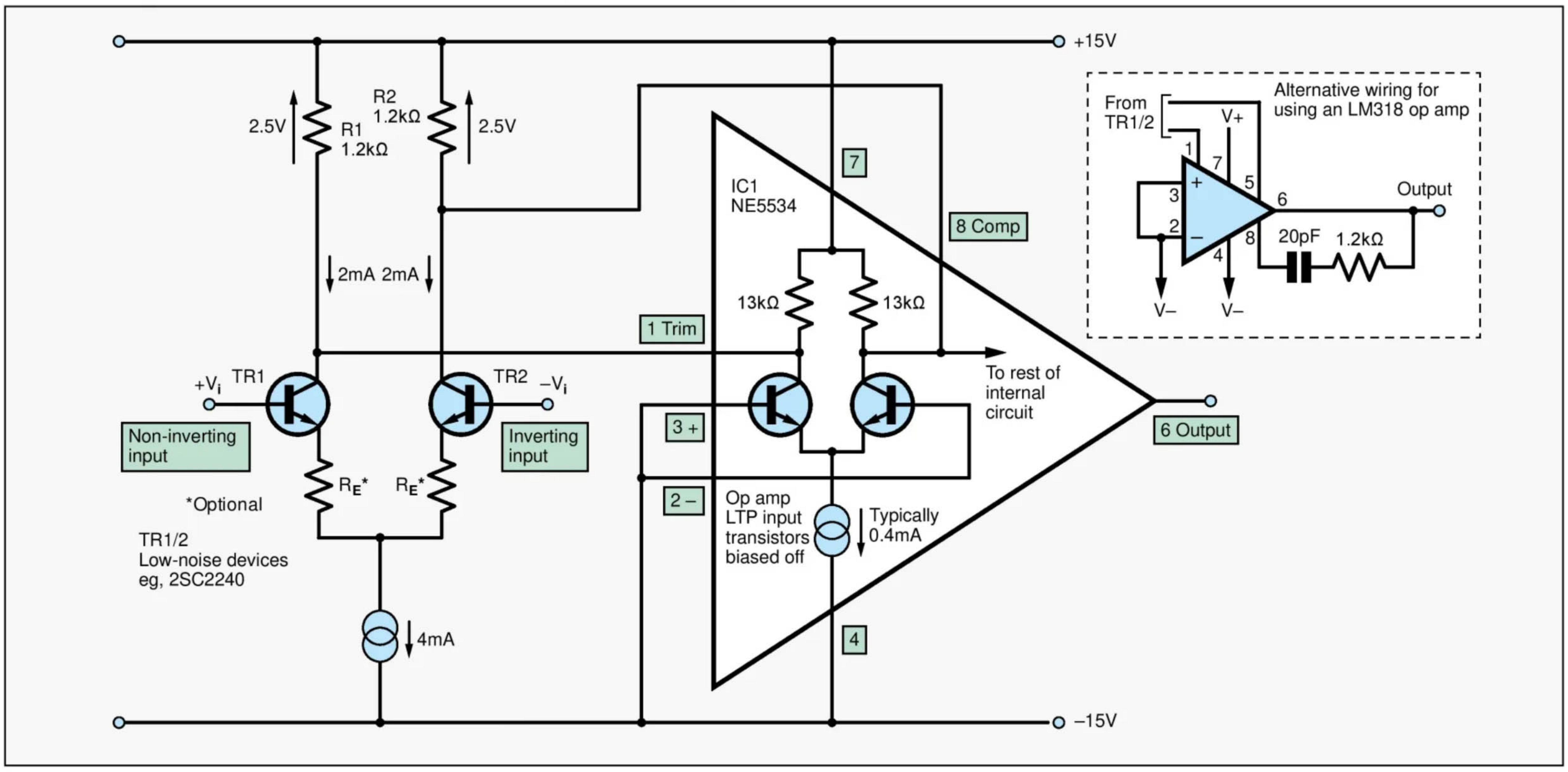

+15V
2.5V
R1
1.2kΩ
R2
1.2kΩ
2.5V
2mA 2mA
+V_i
TR1
TR2
–V_i
Non-inverting input
Inverting input
R_E*
R_E*
*Optional
TR1/2
Low-noise devices
eg, 2SC2240
4mA
IC1
NE5534
7
8 Comp
1 Trim
13kΩ
13kΩ
3 +
2 –
To rest of internal circuit
6 Output
Op amp LTP input transistors biased off
Typically 0.4mA
4
–15V
Alternative wiring for using an LM318 op amp
From TR1/2
V+
Output
20pF
1.2kΩ
V–
V–

Fig.1. Putting discrete transistors in front of an IC op amp to get lower noise. The internal input transistors are biased off by connecting them to the negative rail. The new low-noise transistors are connected to the next stage in the IC via the compensation pins. The LM318 (shown inset) with external input transistors was the only way to get a top-quality audio op amp in the early 1970s.

The simple economics of semiconductors means that the vast majority of modern electronic products are based on ICs (integrated circuits). It's quite rare to see circuits made from individual, separate transistors – what are called 'discrete' designs. Most analogue signal processing systems use IC op amps, which are almost always better than discrete versions, especially for precision instrumentation where the inherent advantages of transistor parameter matching in monolithic devices, and the resulting low DC offset errors, are important.

Audio priorities

However, in audio systems, which are generally AC coupled, DC offset minimisation is less important. Also, very high frequency response is not required. So, a reasonable question is, why pay for a response up to 300MHz when 100kHz is plenty for audio? In fact, output drive headroom, low distortion and low noise are much more important criteria for audio. Given this, the small production runs of top-quality audio equipment and the high price of professional audio op amp chips, it is well worth investigating if discrete design for audio offers any advantages.

First a reminder that the OP and AD series of op amps from Texas Instruments are typically £2.50 to £10 each, and these single-source specialist audio ICs are often hard to source or become 'obsolete' just after you've finished a design! Regular readers of my column will know that there is one low-cost, multi-sourced exception to the problem of expensive, hard-to-find audio-friendly op amps: the NE5534/NE5532, which typically costs under £1. To make a discrete op amp design worth considering, this is definitely the chip to beat. This project will attempt to do just that.

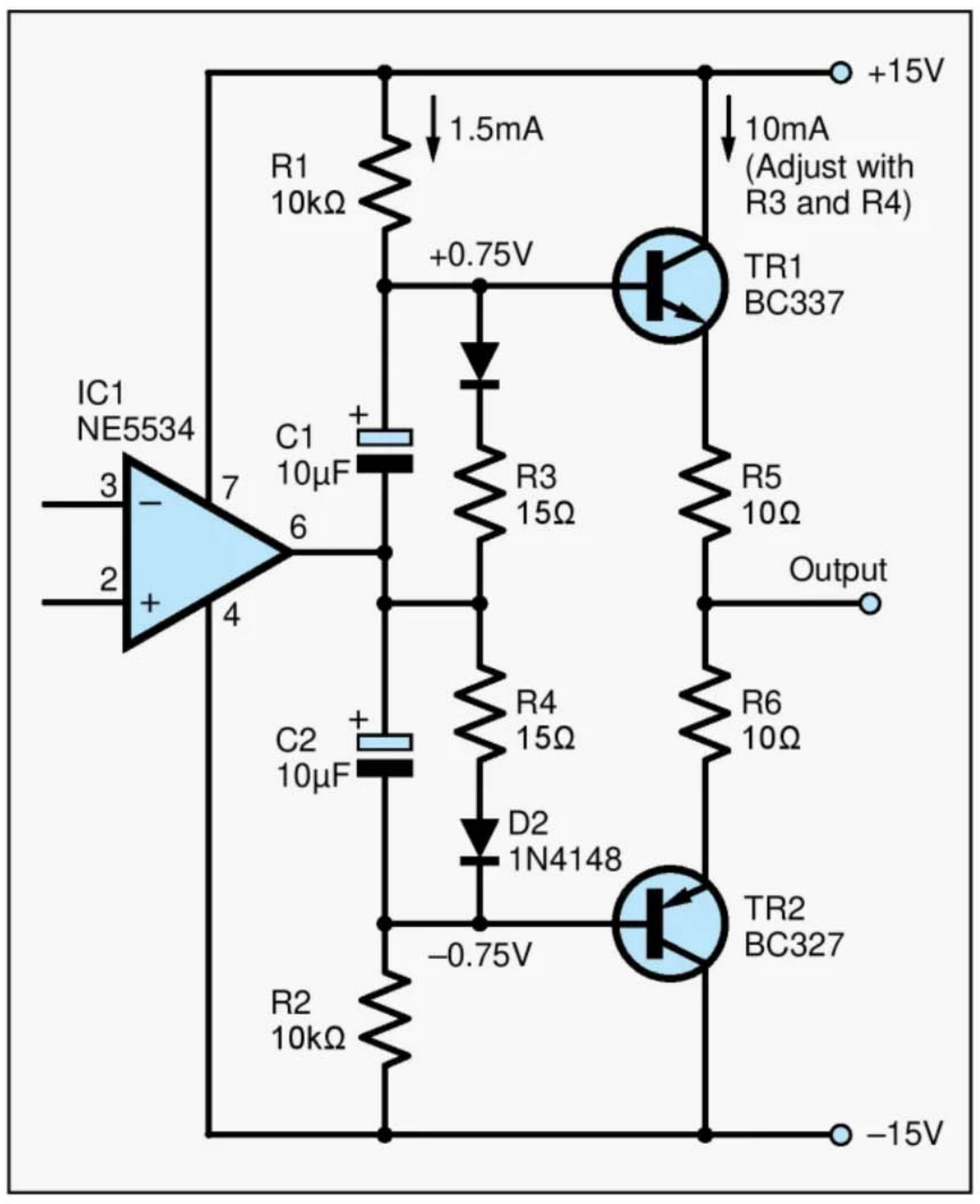

+15V
R1
10kΩ
1.5mA
10mA
(Adjust with R3 and R4)
+0.75V
TR1
BC337
IC1
NE5534
C1
10µF
R3
15Ω
R5
10Ω
3
2
7
6
4
Output
C2
10µF
R4
15Ω
R6
10Ω
D2
1N4148
TR2
BC327
–0.75V
R2
10kΩ
–15V

Fig.2. Boosting the output of an IC op amp with emitter-follower transistors. This is an effective way to get decent drive capability from early audio op amps such as the TL071, which is only happy with loads above 2kΩ.

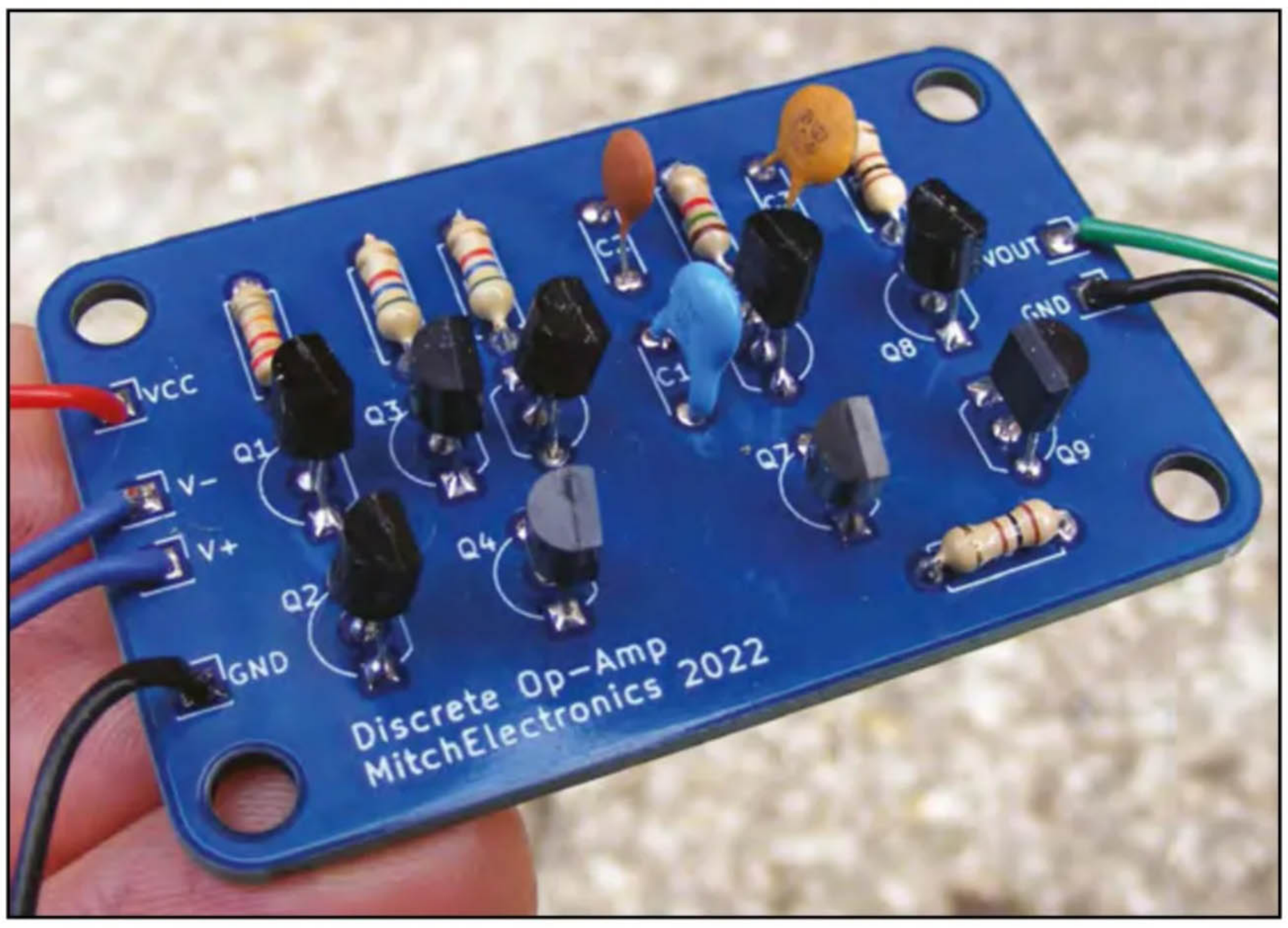


Fig.3. Simple discrete op amp for educational use from mitchelectronics.co.uk. Not Hi-Fi, but excellent for getting started.

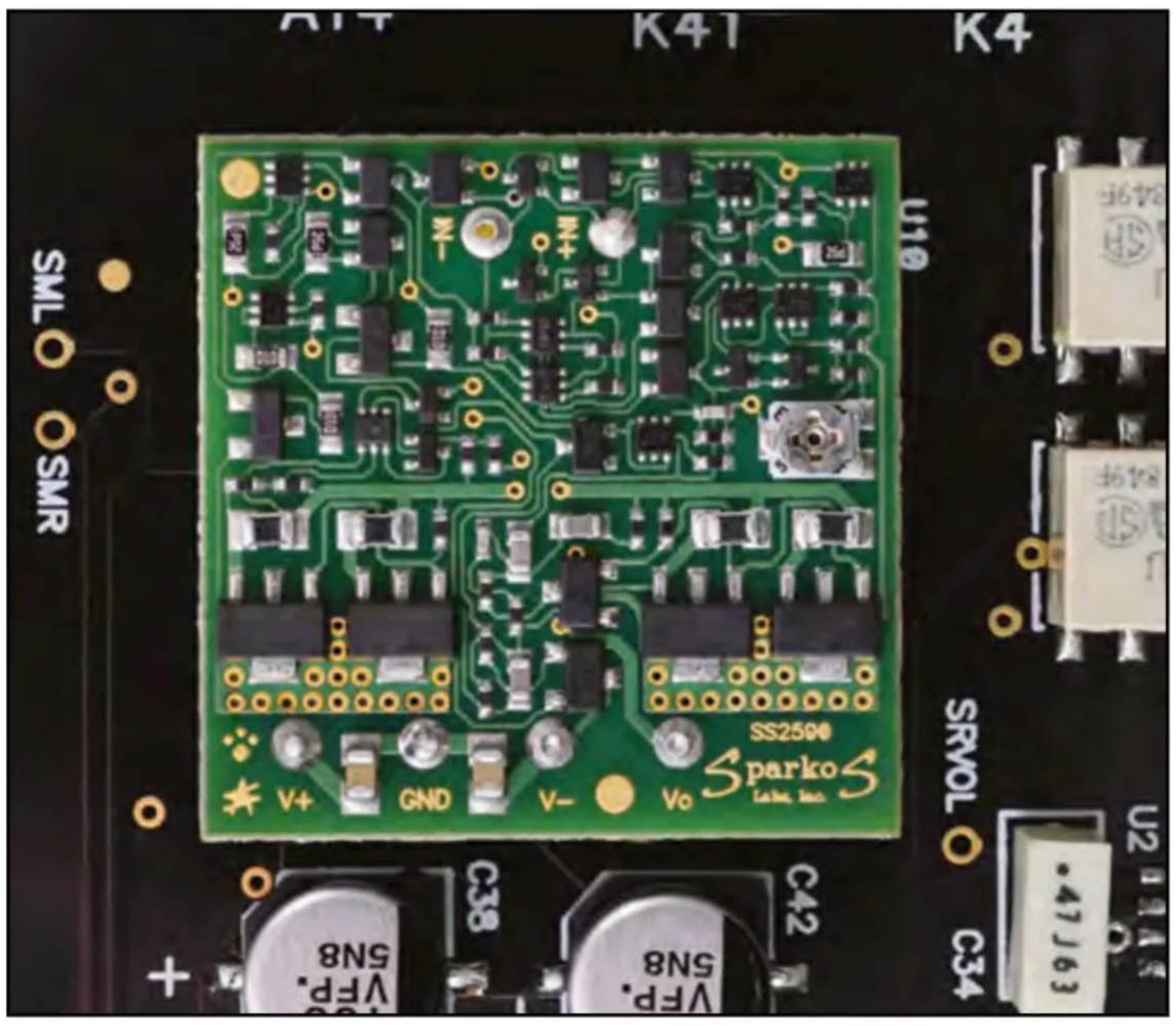


Fig.4. Sparkos Labs, the ultimate discrete op amp?

Hybrid designs

I often use a hybrid approach – sticking discrete transistors on the front end of an IC op amp for lower noise (Fig.1) or adding transistors to the output for higher drive, as shown in Fig.2. While this is often a useful design technique, in the end I thought why not go the whole hog and try to make a purely discrete design to make a proper comparison with integrated versions.

The main bottleneck with the 'hybrid' approach is that the supply voltage is limited by the op amp, typically to ±18V. In fact, with some new op amps, the voltage rating is even less, such as the LM4562 (±17V). This is caused by process developments shrinking the die size, and with it the maximum voltage rating. Discrete, small-signal bipolar transistors such as the BC556 only cost pennies (they haven't suffered the recent price inflation of ICs) but are conservatively rated at 65V. This makes it possible to make a discrete audio op amp with ±24V to ±30V rails for a lower cost than the chip equivalent. True, this price does not factor in labour, but for hobbyists this is much less of a priority – it's a 'labour of love'!

Somewhat surprisingly, with automated surface-mount assembly techniques, a discrete design can now even save money compared to higher-end IC designs. Other advantages discrete has compared to conventional IC fabrication are access to high-gain PNP transistors, low-noise metal thin-film resistors, large-value good-quality capacitors as well as ease of modification and upgradability. These last two factors are particularly relevant to hobbyists – a discrete design offers endless opportunities to tinker, fiddle with and improve a basic design.

elektor
up-to-date electronics for lab and leisure
94
February 1983
75p.
headlamp cross-fader
no-blow fuse
µP telelink
PRELUDE:
the XL control pre-amplifier with facilities:
class-A headphone amp * bus board based *
remote control option * etc

Fig.5. *Elektor* magazine has now moved from audio to Arduino projects. The Prelude was an excellent discrete audio op amp. Mine lasted over 30 years.

Discrete problems

That said, most discrete op amp designs I have built have measured worse than standard chips and I have mainly only used them for educational purposes, such as the kit in Fig.3. It is a real testament to the NE5534 that I have found it very challenging to produce a discrete design that is just as good. The circuit design presented here has similar distortion levels, (but with no high-frequency distortion rise above 10kHz), half the noise, twice the load capacity and ±25V output.

There are plenty of kits online available for discrete op amps, mainly designs based on the venerable Jensen 990 from the US. While these are excellent, they are also expensive. Price aside, a nice aspect to them is that they can be improved upon – for example, the Samuel Groner SGA-SOA-1 upgrade. The Automated Processes API 2520 modules are also very popular, and I've built many Gar2520 kits from Classic Audio Products.

The API pinout seems to have become a de-facto standard for discrete op amps. Fig.4 shows a discrete SMT-built audio op amp from Sparkos Labs. The SS2590 must be one of the highest spec audio op amps ever made – it should be, it uses 40 transistors! I tried to import some, but the distributor couldn't do it for one-offs. (They cost $90 each!)

The *Elektor* Prelude amplifier from 1983 (shown in Fig.5) and Codd's *Wireless World* October 1979 design were both excellent discrete op amps. I suspect these designs formed the basis of Douglas Self's ubiquitous 'Blameless power amplifier'. It's well worth reading Self's detailed analysis of this topology in his *Wireless World* articles on power amp design (1996). This two-gain-stage system (see Fig.6) has formed the basis for several *PE*/*EPE*/*Silicon Chip* designs, such as the *Hifi Stereo Headphone Amplifier* from *PE*, October 2014. It's worth pointing out that this sort of power amp is effectively a power op amp, and it formed an ideal basis for my design. Most specialist IC audio op amps use a three-stage topology, which gets rather complex to implement in discrete circuitry, although the API2520 does it. The NE5534 for example, uses 29 transistors.

Not so discrete

The main practical problem with an all-discrete op amp design is its parts count, with typically a dozen transistors required to get decent performance, as shown in the initial breadboard design in Fig.7. All these connections and complexity do

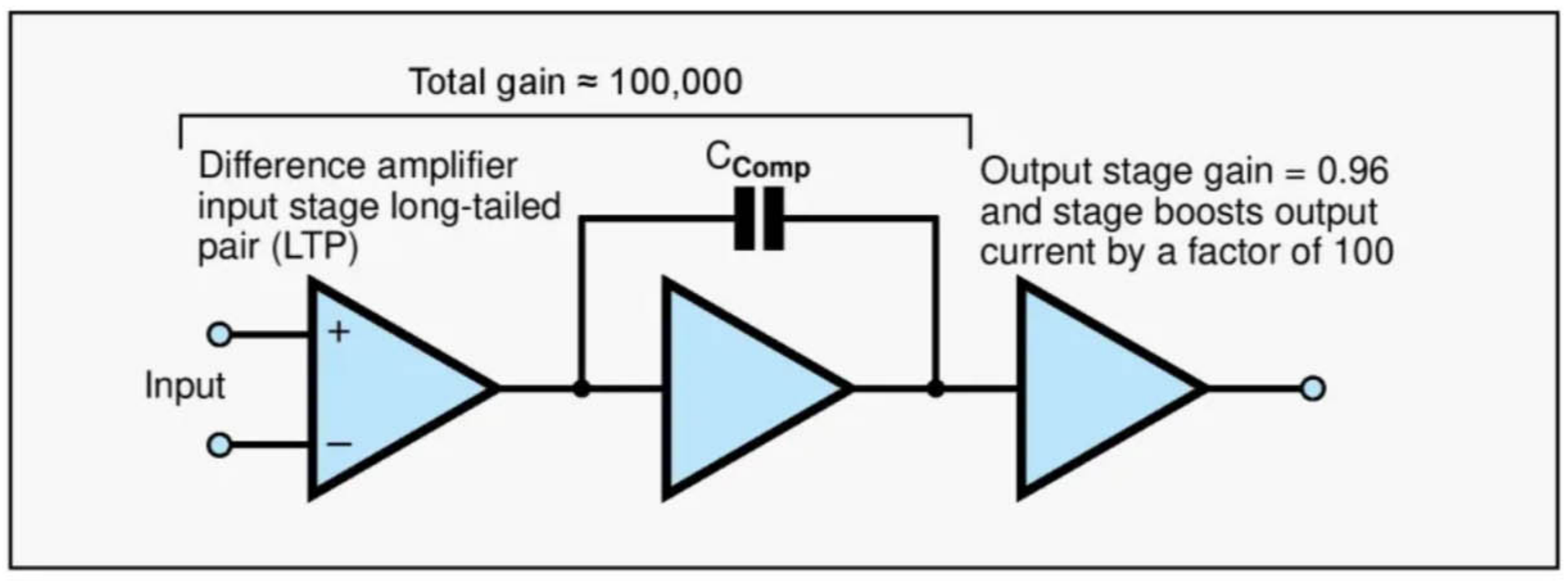

Total gain ≈ 100,000
Difference amplifier input stage long-tailed pair (LTP)
C_Comp
Output stage gain = 0.96 and stage boosts output current by a factor of 100
Input
+
–

Fig.6. Basic structure of a two-gain-stage op amp with difference amplifier, main voltage amplifier and output stage. Note the compensation capacitor, which defines the high-frequency roll off. This has to dominate the roll off since the roll off provided by the transistors is poorly defined.

have an impact on reliability, and I would estimate the mean time between failure of a discrete op amp is over ten-times worse than for an equivalent IC version. Therefore, I wouldn't recommend using a discrete op amp for any system-critical application such as avionics, but elsewhere, say in a recording studio environment, they are certainly viable, providing they use standard commodity parts. (Interestingly, the first UK solid-state Hi-Fi amplifier from Toby Dinsdale (1964) started off as an avionic servo op amp.)

Another discrete-design problem is that discrete transistors have not improved much in the last 30 years, which means old Mullard/Philips workhorses, like the BC549 and BD139 from the 1970s are still used. After Europe gave up transistor development, Japanese companies, particularly Toshiba and Sanyo, continued improving their through-hole bipolar discrete transistors until the end of the 1990s. Their new 2SA/B/C devices, which were developed for the large Japanese Hi-Fi amplifier industry became highly sought after. Sadly, this progress has also stopped, and further process improvements were directed towards ICs, giving chips a further edge.

Excellent versions of Japanese-designed transistors are still being produced in Korea by Unisonic Technologies Co. (UTC) with the prefix 'KT' rather than '2S'. Some of these can still be obtained from Profusion Plc and Tayda, but these are gradually being dropped. This has led to the usual eBay situation of exorbitant prices and fake Toshiba devices for the unwary.

Closer to home, some discrete development continued for a while in the UK with the Ferranti 'Zetex' or ZTX transistor range, which have been popular with audiophiles. These are now made by Diodes Incorporated.

The overall small-signal transistor development plateau led John Little from Little Labs to use surface-mount output driver chips in his Monotor headphone amplifier (Fig.8). Unfortunately, I can't find out which SMD devices he used – very frustrating!

As you can tell from this somewhat extended introduction, the discrete vs integrated debate is complicated. For home constructors though, I firmly believe a (well-designed) discrete op-amp-based design is still the best option for a top quality Hi-Fi headphone, phono or microphone amp.

Op amp 101

Building a discrete op amp is a great way to learn about the internal operation of all op amps and see what is really going on under the hood. Let's look at the internal stages and get a feel for how they operate and some possible optimisations.

When it comes to explaining basic op amp negative feedback linear operation, I always say, 'the output voltage steers itself to make the voltage difference between the two input terminals zero'. The network in the feedback path from the output to the inverting input then dictates what the system does. For example, if the attenuation in the feedback network is a factor of 10, then the output will have to be 10-times bigger than the input to keep the two input terminals the same. Thus, we will have made an amplifier with a gain of 10. For this system to work predictably we have to assume 'ideal' op amp characteristics – ie, the open-loop gain is infinite, no current is drawn by the inputs and the output has zero source resistance.

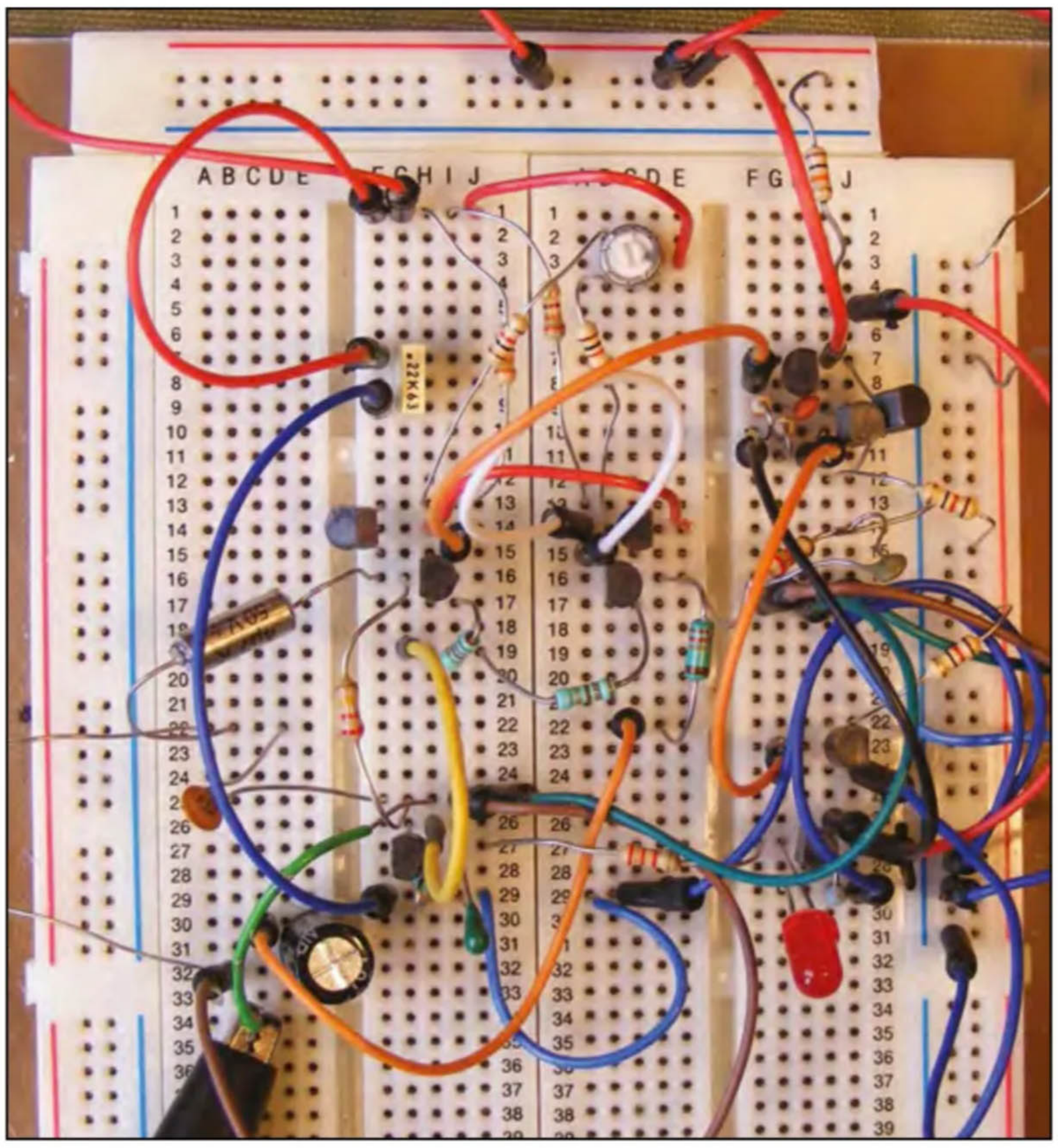


Fig.7. A busy breadboard – 12 transistors is about the limit for me before jumpy connections become a problem.

I'll now work my way through each of the stages of a conventional op amp.

The difference amplifier

The fundamental architectural feature of an operational amplifier is its differential input. That is, it has two inputs called 'non-inverting' and 'inverting', where the difference between the two is the voltage to be amplified. A differential input means the circuit can be configured to perform many types of operations – for example, multiplication (amplifying), summation (mixing), subtraction (input balancing) and lots of other analogue functions or mathematical operations.

The difference amplifier is usually based on Blumlein's famous long-tailed pair (LTP) configuration, which he patented in 1936. He originally used triode valves, but today the most common arrangement is a pair of NPN bipolar transistors (or N-channel FETs) as shown in Fig.9.

To minimise DC offset and distortion, the two devices need to be well matched in terms of transconductance. That is, how much collector current flows for a given base-emitter voltage

stereo
R/L
L/R
mono
L+R
L
R
phase
L-R
headphone outs
level
Labs
tor
analyzing
hone amp

Fig.8. The Little Labs Monotor headphone amplifier – a wonderful design, but I can't fix it due to single-sourced SMT output chips

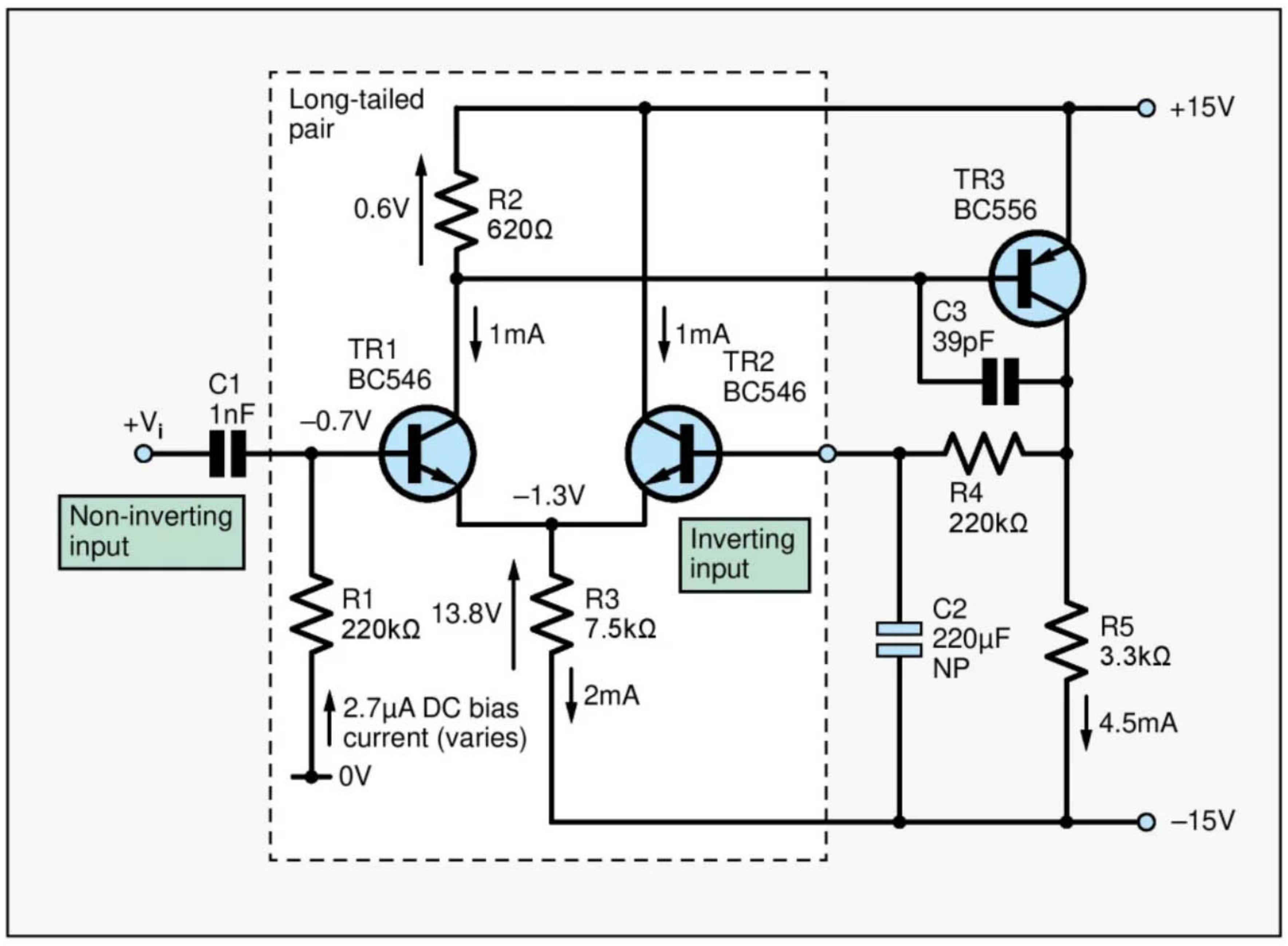


Fig.9. The Blumlein long-tailed pair (LTP), outline dotted, originally designed to replace transformers so that much higher bandwidths were possible. It can use bipolar transistors, FETs or the original triodes (the ECC88 works well at 90V) for the input devices. The circuit here is the simplest 'op amp' one can make. It's open-loop gain is 3000. The feedback resistor (R4) is completely decoupled by C2 so that the open-loop gain can be measured.

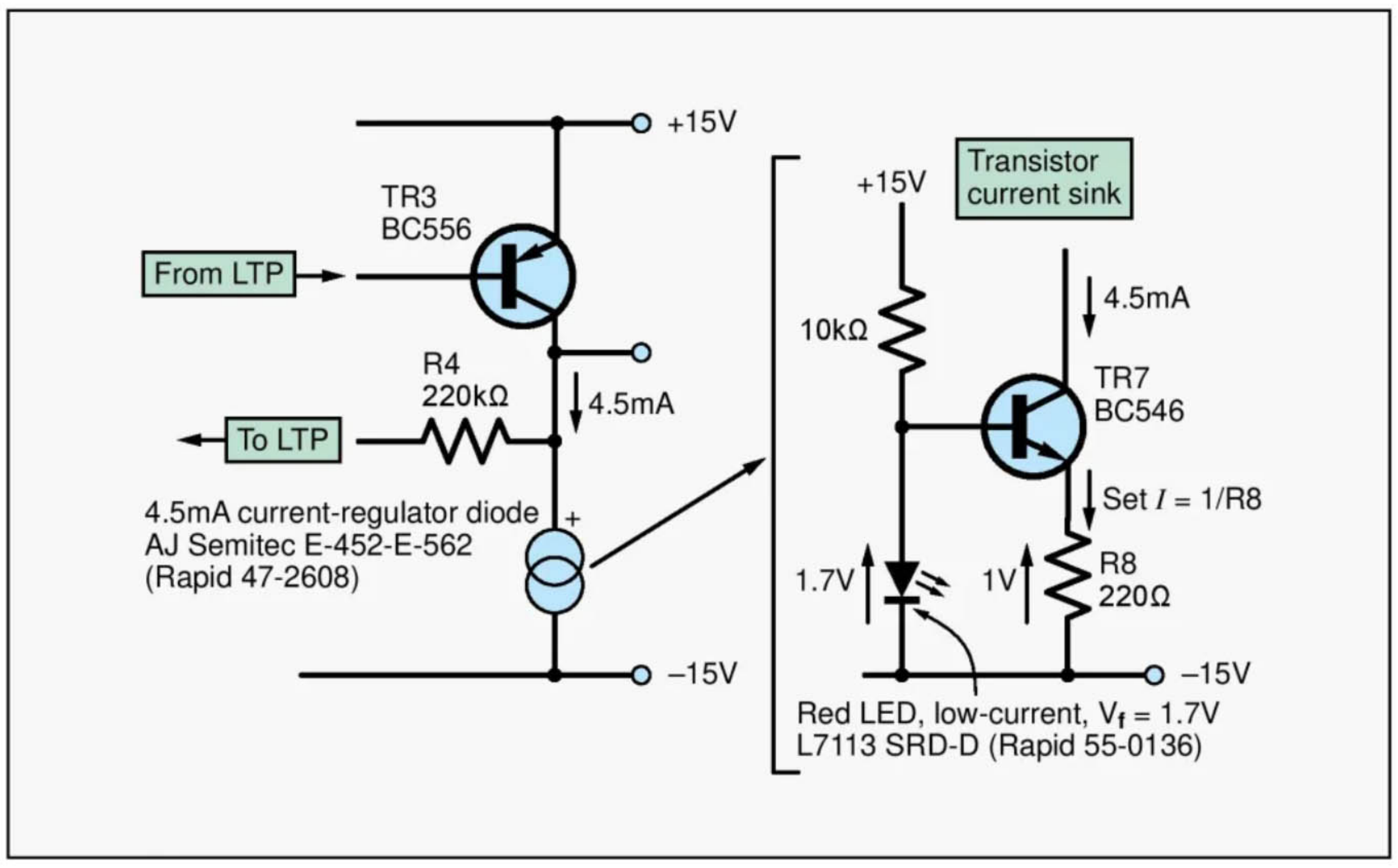


Fig.10. Adding a constant-current load (sink) to the voltage amplifier stage TR3 bumps the gain up to 12,500. Note 'upside-down' PNP arrangement. For comparative purposes, I swapped out the resistor for a current-regulator diode before replacing that with a biased transistor TR7.

expressed in mA/V. The current gain (H_{fe}) is of less importance, unless high source resistances are used. The transistors can be hand matched with a multimeter or analyser, such as those made by Peak Electronic Design (see back cover!).

The best approach is to use a dual transistor, such as the SSM2210 – popular but pricey – so not appropriate for this high-quality, low-price design. Toshiba introduced some surface-mount audio dual-transistors in 2001, such as the 50V HN1C01FY. We will have provision on the PCB for these. They are available from Mouser for around 30p.

One historical detail worth mentioning is that in the 1970s, PNP transistors were preferred over NPNs for LTP circuits since they have a slightly lower base spreading resistance, resulting in a lower noise level. This difference is much smaller today, so we'll use NPN types for our LTP since there is much more device choice.

FET inputs

Fabricating JFETs instead of bipolar transistors in LTPs has been used in op amp IC designs. It offers the advantage of having a very high input impedance, fulfilling one of the key criteria for an ideal op amp. In audio applications, the bias currents from bipolar transistor inputs (see R1, Fig.9) mean that potentiometers have to be AC coupled to prevent scratching. However, normal JFETs have about 40-times less transconductance than bi-polar transistors, which means twice as much distortion.

There are esoteric audio JFETs available, such as the 2SK170 and 2SJ74 which achieve high transconductance, at a high cost. Also, there are good Toshiba SMT devices, such as the 2SK2145. This device has its two sources connected together and brought out on one pin, which is fine for our LTP purposes. As an aside, it's worth noting that it's difficult to process FETs at the same time as bipolar devices on the same IC, which makes low-noise audio FET op amps expensive. On the other hand, with discrete op amps, you can just solder them in.

Constant-current sources and sinks

For audio work, the current needed through each LTP input device generally has to be higher than 1mA for low noise from low source impedances. (There are however higher impedance applications, such as moving magnet pick-up cartridges, that may need lower currents). This means the collector load resistors (R3 and R5, Fig.9) have to be low value, resulting in low gain. Replacing the resistors with current sources gives the current required but with a high effective dynamic impedance, greatly increasing gain.

Using a current source has an additional benefit of an increased power supply rejection ratio (PSRR) since the current remains constant with power supply fluctuations. Current regulator diodes are the simplest way of doing it, needing no bias supply. For R&D use they are excellent since they just fit in a standard resistor position. However, as a carefully selected gate-source coupled JFET, they have become rather expensive. It's much cheaper to use the standard transistor design. I found replacing the tail resistor (R3) with a current source in Fig.9 only increased the gain to 3500, but it did make the tail current independent of supply voltage. (With just a resistor, the current is proportional to the supply voltage, an unwanted variable.)

The noise from the tail current source, although higher than a resistor, is not a problem since it is common mode – it's applied to both LTP input transistors equally and thus cancelled. One of the great advantages of a discrete op amp is that bias voltages for the current sources can be easily accessed and decoupled with large capacitors for low noise.

Voltage amplifying stage (VAS)

The bulk of our system voltage gain is provided by the voltage amplifying stage (VAS), which is based on a common-emitter strapped between the two power rails, as shown in Fig.10. The term 'VAS', as coined by Douglas Self, is really a misnomer since it has a current input. Again, a constant current load here can provide higher gain and better DC stability. In Fig.9, replacing the collector load resistor R5 with a 4.5mA current-regulating diode (CRD) increased the gain to 12,500 (from 3500).

Sometimes, for higher output voltage swings, a bootstrap capacitor is used. A current source typically drops around 1.5V, so it is worth bootstrapping it in low voltage applications.

The load impedance on the VAS stage output is important. If it is too low the open-loop gain will drop and the gain advantage of the constant-current sink will

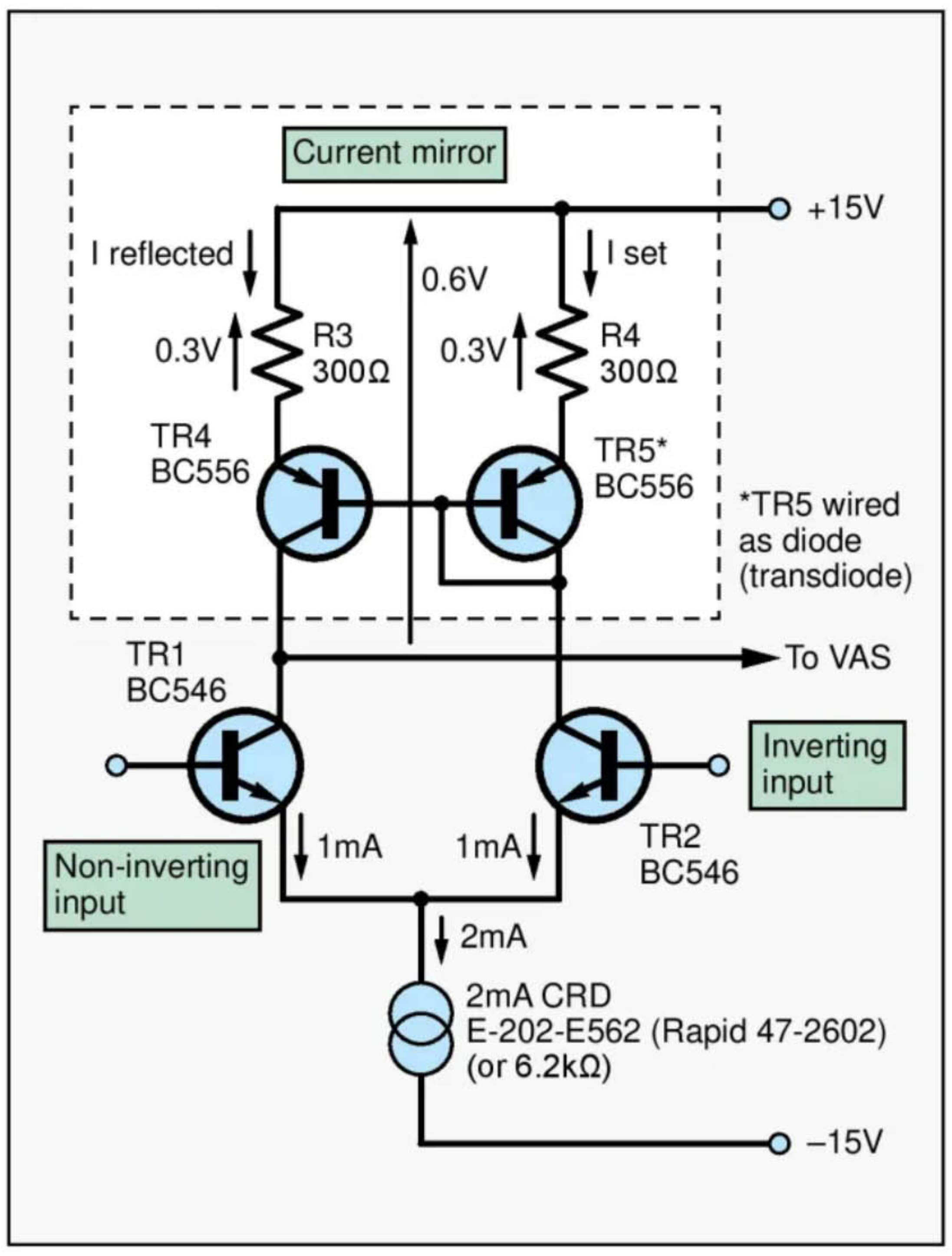


Fig.11. A current mirror on the LTP equalises the current and increases gain further to around 150,000 (without emitter resistors).

be lost, bringing us back to the position of just using a load resistor again. This problem also applies to a lesser extent to the LTP current mirror output loading. This effect can be minimised by using a high H_{fe} transistor (>450) for TR3. Unfortunately, we need a V_{ce} rating of at least 50V, and most normal high-gain transistors such as the BC559C are around 30V.

It's all done with mirrors

A current mirror comprising TR4 and TR5 can be used to enforce the same current through both LTP transistors, reducing the need for close matching of TR1 and TR2, see Fig.11. This circuit has a push-pull action, with the current on one side reflected in the other, so the transconductance is doubled for a given current. This and the high dynamic load results in a gain increase of around 10 compared to a resistive load. Putting the current mirror into Fig.9 increased the gain to around 150,000 at 1kHz. We are now in the realms of 'proper' op amps with an open-loop gain of around 100dB. The gain does roll off towards high frequencies due to Miller effect in the transistors, (the magnification of base-collector capacitance).

Of course, the current mirror can itself be mismatched. The inclusion of emitter resistors in the mirror (R3 and R4 in Fig.13) reduces the effect of transistor mismatching. A voltage drop across these resistors of 0.3V provides sufficient negative feedback to equalise the mirror currents. This is also a place to insert a DC offset trimmer to set the quiescent voltage of the op amp output to zero. When using discrete transistors for TR1, TR2, TR4 and TR5, this offset is worse due to transistor mismatching, so adjustment is often needed.

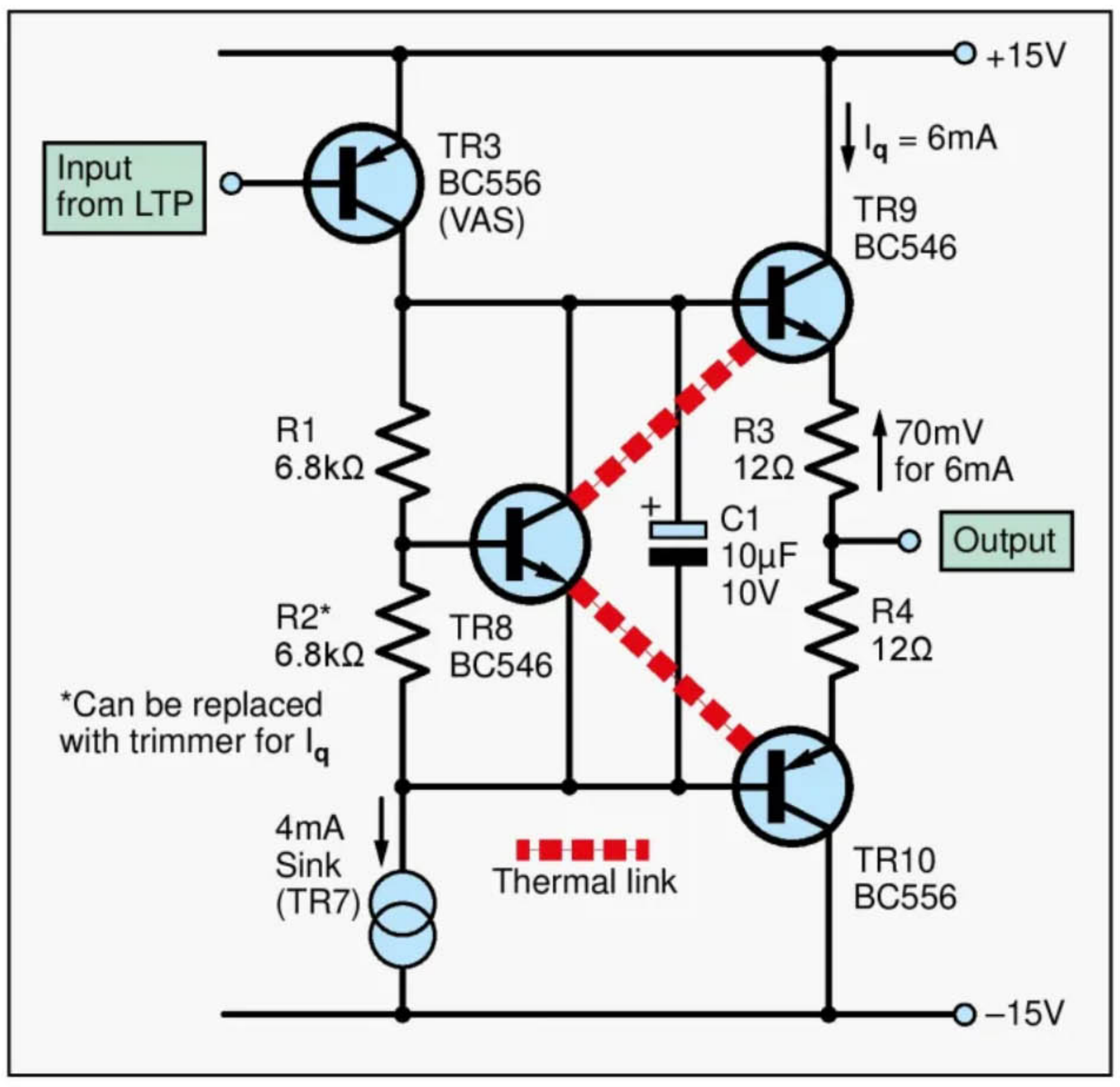


Fig.12. Emitter-follower output stage. In this case a fixed bias is used in conjunction with large emitter resistors R3 and R4. Often R2 has a series trimmer to allow quiescent current adjustment. This will drive loads down to 300Ω. If lower impedance 100Ω loads are to be driven, the output transistors will have to be upgraded to ZTX651/751 and provided with heatsinks. Loads below this, such as 32Ω headphones, will need extra output transistors (see next month).

Compensation

All negative feedback circuits need compensation to prevent high-frequency oscillation. This limits the closed-loop gain to unity at the frequency where 180° phase shift occurs, preventing positive feedback. This phase-shift is a result of high-frequency losses in the transistors, mainly the slower output transistors. The simplest way to fix this problem is to set a dominant defined roll-off by wiring a small NP0 ceramic capacitor (C3) of around 22pF to 100pF across the base-collector junction of the VAS transistor TR3, depending on the closed-loop gain.

It is difficult to determine the optimum value for this component. Too much, and your high-frequency distortion is higher than it needs to be. Too low, and the odd amplifier may oscillate in production. One advantage of discrete over chips is that you can optimise this capacitor to suit your particular transistors and layout. For this design, 39pF was used for 10-times gain and 82pF for unity gain. Another trick is to use two capacitors to get second-order compensation (This is not an option on ICs because the bigger second capacitor would use too much die area.)

Baxandall found it useful to add an additional compensation feed from the output stage. He called it 'inclusive Miller compensation'. This did not make much difference with a low-power op amp, possibly because the small output transistors did not make such a big crossover glitch. However, it does make a difference at higher powers and will therefore be included on the PCB as an option.

Emitter resistors

The maximum input into a bipolar LTP before noticeable soft-clipping distortion occurs, is around 50mV$_{pk-pk}$. (Of course, the actual signal, the error voltage, is only a couple of mV in most negative feedback situations). The way round this is to install emitter resistors (R1 and R2) to provide local negative feedback. A good analysis of bipolar transistor distortion was given by WT Cocking in *Wireless World*, May 1972. These resistors reduce the gain by around 10x, but this can be compensated to a degree by increasing the operating current of the LTP.

This gain reduction is useful where the current mirror is used as a collector load for the LTP, since there is generally too much. Reducing the gain by a factor of 10 enables the compensation capacitor to be reduced by 10. This then presents a higher impedance load at high frequencies (>10kHz), reducing the possibility of the input stage overloading. This slewing distortion is an issue when high output voltage at high frequencies is required. It manifests itself when a 20kHz sinewave becomes a lopsided triangle wave.

A problem with these emitter resistors (R1 and R2) is that they add Johnson noise. This becomes an issue where high closed-loop gain is required at low impedances, such as in a mic or moving-coil phono pre-amplifier. The input signal here is low, therefore distortion is minimal, so it's best to leave the resistors out. With JFETs these resistors are not used, since the transconductance is low and we need all the gain available.

A low-noise upgrade for the input stage LTP transistors (TR1, TR2, TR4 and TR5) is to use the 2SA970 and its complement the 2SC2240. These are rated at 120V and have a noise factor of 0.5dB.

Output stage

The output stage is a voltage follower or current amplifier. In most op amps this is a class AB push-pull emitter follower, as shown in Fig.12. The VAS stage can comfortably drive this for low powers down to 300Ω. For higher power, extra high-current output transistors in a Darlington stage could be used. This is the best option for a high power op amp, such as a transformer or headphone driver. These high power output stages add another couple of output transistors, and the original output transistors become driver transistors.

Thermal stability

The output stage normally has a preset quiescent current, set to typically 3-15mA to reduce crossover distortion. In discrete circuits we have the option to increase this to 100mA to ensure class A operation for minimum distortion. This current will increase as the output stage heats up, and failure due to thermal runaway is likely unless effective heatsinks and stabilisation is used. Normally, a V_{be}-multiplier bias transistor (TR8) is thermally coupled to track the temperature. It's also bypassed by a capacitor (C4) to ensure equal drive to both output transistors. This set-up is easier to arrange with discrete circuits. On integrated circuits the whole chip gets cooked. However, in a high-power design using the CFP output stage, only the drivers need be coupled to the bias generator.

Protection racket

All output stages need output short-circuit protection in the form of current limiting. A dodgy lead or slipped probe is all it takes to destroy the VAS and output transistors. In its simplest form, this can be high-value output emitter resistors of a few tens of ohms or a series output resistor. This of course raises the output impedance and causes loss of headroom. A better approach is to provide current sensing on the emitter resistors or power rails. One quirk of the circuit developed here is that shorting out the LED voltage reference for the current sources turns the whole thing off. This allows it to have a 'shutdown pin' for protection purposes. It also turns off if either power rail is lost since the LED is wired between the two rails. Using this approach, a rather crude protection circuit has been devised which allows 300Ω to be driven while shutting it off below 100Ω.

The final discrete op amp circuit is shown in Fig.13. It uses low-cost BC546/56 devices. A nice feature of discrete circuits is that if you blow them up it's usually only a few cheap transistors and resistors that are easily replaced; with an expensive chip, that's it. However, it's easier to damage the discrete circuit because it's impractical to provide the full protection circuitry available to the IC designer, such as thermal shutdown.

Odd-ball op amp

Last, an unconventional approach shown in Fig.14, which we will *not* be using on the circuit's PCB. This design shows how audio op amps can depart from the more conventional design shown in Fig.13. It is possible to make an op amp with a difference amplifier comprising *one* transistor, which can save cost if an expensive device for TR1, such as a 2SJ74 FET is needed. Single-ended stages have higher even-order distortion since there isn't the cancellation of two curved transfer characteristics (as with the LTP). There is also a bad DC offset due to the V_{be} drop of the transistor and drop across the feedback resistor, (since the full stage current has to flow through it). This is not a problem in single-rail audio applications with low-value feedback resistors. It has the significant advantage of giving a 3dB lower noise level than the differential pair.

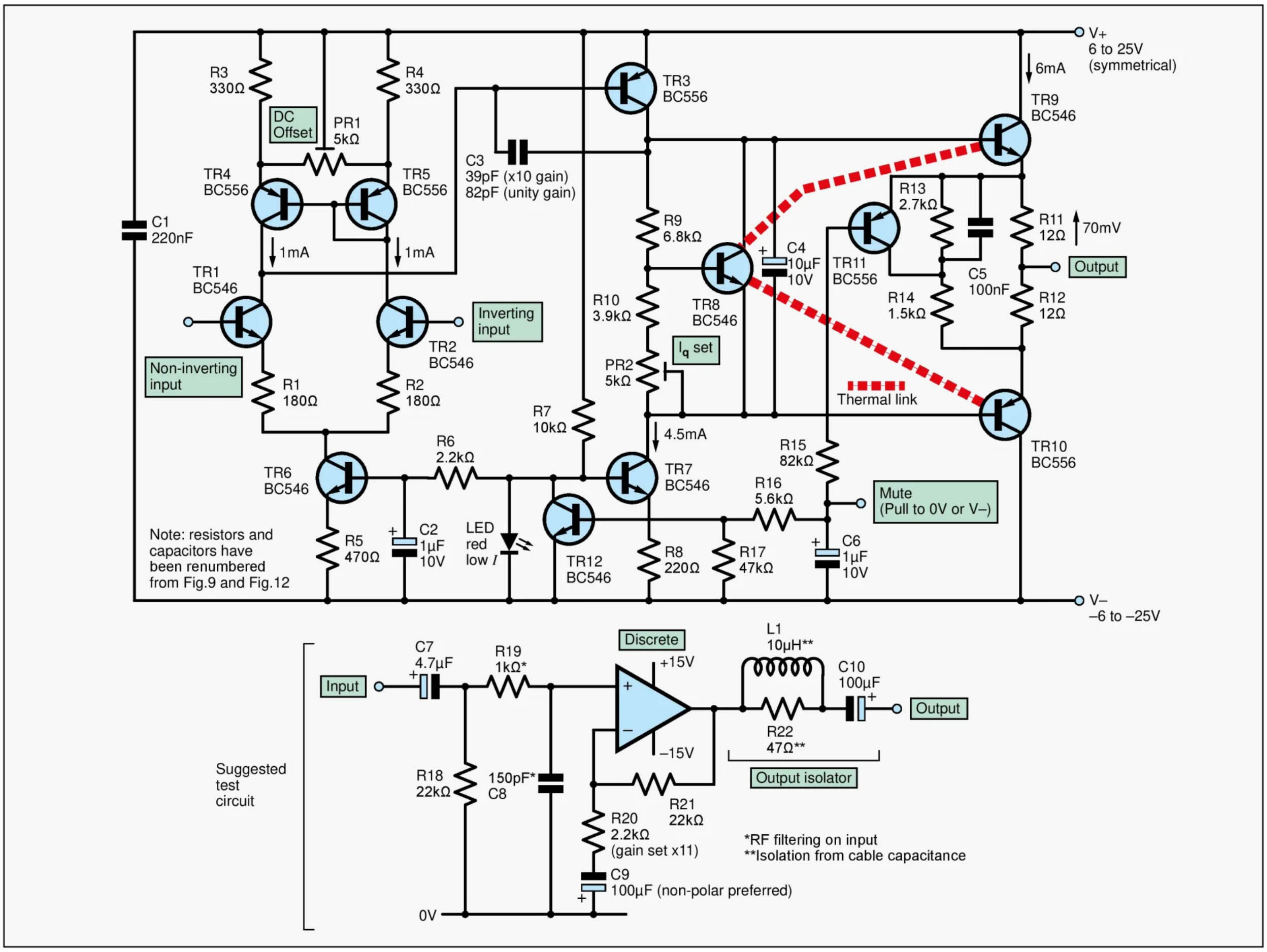

V+
6 to 25V
(symmetrical)
R3
330Ω
R4
330Ω
DC
Offset
PR1
5kΩ
TR3
BC556
6mA
TR9
BC546
C3
39pF (x10 gain)
82pF (unity gain)
TR4
BC556
TR5
BC556
C1
220nF
1mA
1mA
R13
2.7kΩ
R9
6.8kΩ
R11
12Ω
70mV
C4
10µF
10V
TR11
BC556
C5
100nF
Output
TR1
BC546
Inverting
input
R10
3.9kΩ
TR8
BC546
R14
1.5kΩ
R12
12Ω
TR2
BC546
Iq set
Non-inverting
input
R1
180Ω
R2
180Ω
PR2
5kΩ
Thermal link
R7
10kΩ
4.5mA
TR10
BC556
R6
2.2kΩ
R15
82kΩ
TR6
BC546
TR7
BC546
R16
5.6kΩ
Mute
(Pull to 0V or V–)
C2
1µF
10V
LED
red
low I
R5
470Ω
TR12
BC546
R8
220Ω
R17
47kΩ
C6
1µF
10V
Note: resistors and
capacitors have
been renumbered
from Fig.9 and Fig.12
V–
–6 to –25V
Discrete
L1
10µH**
C7
4.7µF
R19
1kΩ*
+15V
C10
100µF
Input
Output
–15V
R22
47Ω**
Suggested
test
circuit
R18
22kΩ
150pF*
C8
Output isolator
R21
22kΩ
R20
2.2kΩ
(gain set x11)
*RF filtering on input
**Isolation from cable capacitance
C9
100µF (non-polar preferred)
0V

Fig.13. Nearly there now, the full op amp circuit. Emitter resistors R1 and R2 have been added to the LTP, reducing the stage gain and linearising it, making it easier to prevent HF oscillation. Also, DC offset PR1 and I_q trimmers PR2 have been added. The final PCB will have some minor enhancements to make it more versatile. There will also be provision for feedback components for basic non-inverting and inverting configurations, as shown in the test circuit.

Cascoding

This unusual op amp design also uses a cascode in the VAS in Fig.14. This is a special technique that places a common-base amplifier (TR7) in series with a normal common-emitter (TR2) to make a 'super' transistor from two cheap devices. This topology improves high-frequency response by eliminating modulation from the Miller effect (high frequency attenuation) and Early effect (distortion), giving much lower overall high-frequency distortion. It allows a low-voltage high-gain device to be used for the lower transistor (TR2) and a higher-voltage general-purpose device (TR7) for the upper transistor. It does require a bias voltage of around 2.7V to 4.7V provided by Zener diode D4. Cascoding can also be used with LTPs, enabling the use of low-voltage FETs for the input devices. This was done on the phono pre-amp on the Pioneer SX-1980 amp using ±34V rails. Cascoding could be a later upgrade for Fig.13.

Next month, we'll make a full discrete through-hole op amp with construction details and test results.

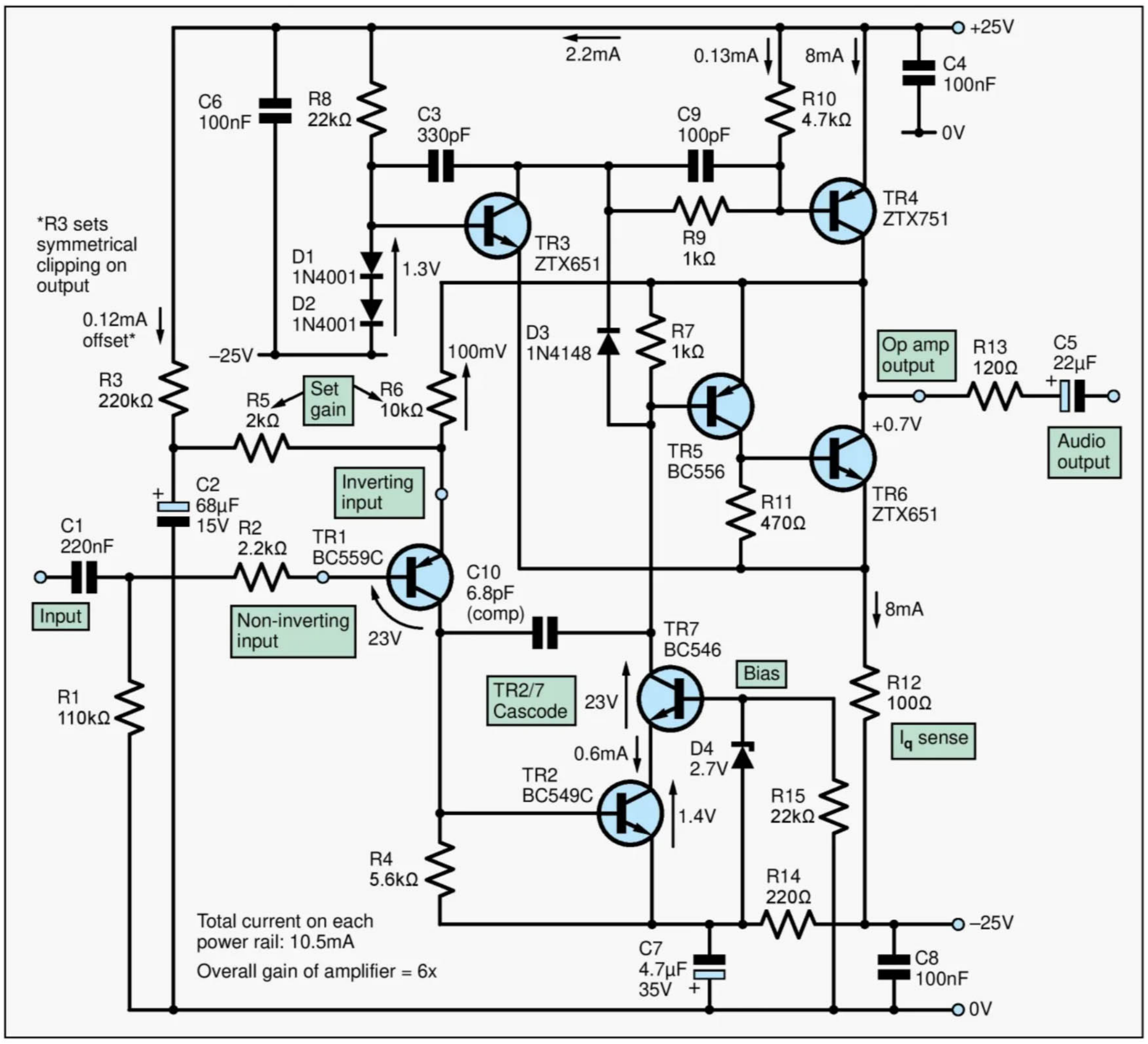

+25V
2.2mA
0.13mA
8mA
C4 100nF
0V
C6 100nF
R8 22kΩ
C3 330pF
C9 100pF
R10 4.7kΩ
TR4 ZTX751
R9 1kΩ
TR3 ZTX651
*R3 sets symmetrical clipping on output
D1 1N4001
D2 1N4001
1.3V
0.12mA offset*
–25V
100mV
D3 1N4148
R7 1kΩ
Op amp output
R13 120Ω
C5 22µF
R3 220kΩ
R5 2kΩ
Set gain
R6 10kΩ
TR5 BC556
+0.7V
Audio output
C2 68µF 15V
Inverting input
R11 470Ω
TR6 ZTX651
C1 220nF
R2 2.2kΩ
TR1 BC559C
C10 6.8pF (comp)
Input
Non-inverting input
23V
8mA
TR7 BC546
Bias
R12 100Ω
R1 110kΩ
TR2/7 Cascode
23V
I_q sense
0.6mA
D4 2.7V
TR2 BC549C
1.4V
R15 22kΩ
R4 5.6kΩ
R14 220Ω
Total current on each power rail: 10.5mA
Overall gain of amplifier = 6x
C7 4.7µF 35V
C8 100nF
–25V
0V

Fig.14. Single-input transistor op amp derived from a design originally developed for Avondale Audio, who eschew LTP inputs. The VAS stage is a cascode which brings HF distortion down to 0.001%. The Taylor configuration output stage has self-regulating quiescent current, See *Audio Out*, Aug 2016.

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HP6632B	PSU 0-20V 0-5A	£195
HP6644A	PSU 0-60V 3.5A	£400
HP6654A	PSU 0-60V 0-9A	£500
HP8341A	Synthesised Sweep Generator 10MHz – 20GHz	£2,000
HP83630A	Synthesised Sweeper 10MHz – 26.5 GHz	POA
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HP8484A	Power Sensor 0.01-18GHz 3nW-10µW	£75
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HP8563A	Spectrum Analyser Synthesised 9kHz – 22GHz	£2,250
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Marconi 2030	Synthesised Signal Generator 10kHz – 1.35GHz	£750
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Marconi 2440	Counter 20GHz	£295
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Marconi 2955	Radio Communications Test Set	£595
Marconi 2955A	Radio Communications Test Set	£725
Marconi 2955B	Radio Communications Test Set	£800
Marconi 6200	Microwave Test Set	£1,500
Marconi 6200A	Microwave Test Set 10MHz – 20GHz	£1,950
Marconi 6200B	Microwave Test Set	£2,300
Marconi 6960B	Power Meter with 6910 sensor	£295
Tektronix TDS3052B	Oscilloscope 500MHz 2.5GS/s	£1,250
Tektronix TDS3032	Oscilloscope 300MHz 2.5GS/s	£995
Tektronix TDS3012	Oscilloscope 2 Channel 100MHz 1.25GS/s	£450
Tektronix 2430A	Oscilloscope Dual Trace 150MHz 100MS/s	£350
Tektronix 2465B	Oscilloscope 4 Channel 400MHz	£600
Farnell AP60/50	PSU 0-60V 0-50A 1kW Switch Mode	£300
Farnell XA35/2T	PSU 0-35V 0-2A Twice Digital	£75
Farnell AP100-90	Power Supply 100V 90A	£900
Farnell LF1	Sine/Sq Oscillator 10Hz – 1MHz	£45
Racal 1991	Counter/Timer 160MHz 9 Digit	£150
Racal 2101	Counter 20GHz LED	£295
Racal 9300	True RMS Millivoltmeter 5Hz – 20MHz etc	£45
Racal 9300B	As 9300	£75
Solartron 7150/PLUS	6½ Digit DMM True RMS IEEE	£65/£75
Solatron 1253	Gain Phase Analyser 1mHz – 20kHz	£600
Solartron SI 1255	HF Frequency Response Analyser	POA
Tasakago TM035-2	PSU 0-35V 0-2A 2 Meters	£30
Thurlby PL320QMD	PSU 0-30V 0-2A Twice	£160 – £200
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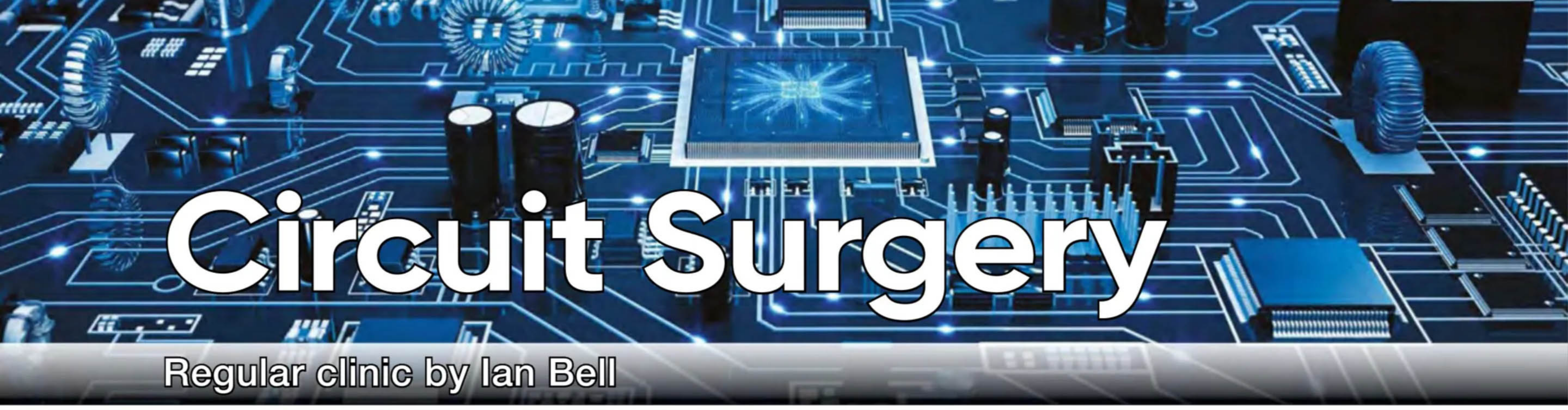


Circuit Surgery

Regular clinic by Ian Bell

Gyrators

A recent post on the EEWeb forum asked about converting a low-frequency square wave (around 7Hz) to a sinusoid. At the time of writing, as was pointed out by one of the replies, few details of the requirements were available (eg, frequency range) so it was difficult for respondents to give much advice beyond general suggestions about filtering. However, one reply mentioned possible use of a gyrator circuit, which is something we have not looked at before. So, this month we will discuss gyrators. Gyrators are very useful in some filtering applications, particularly the filters in equalisers used in audio applications. Gyrators are also used in analogue telephones and some RF systems to separate AC signals from DC (power).

Gyrators are part of a range of circuits that can be generally described as 'impedance converters'. They have specific names, such as Negative Impedance Converter (NIC), General Impedance Converter (GIC) and Frequency-Dependent Negative Resistor (FDNR). NICs can take an impedance and convert it to its negative – so applied to a resistor *R*, the NIC circuit behaves like a resistor of value –*R*. Circuits such as these are used quite frequently by integrated circuit designers, but they are probably less common in discrete circuit design.

Converting capacitors to inductors

The most important property of gyrators in general circuit design is that they can be used to create circuits that behave like inductors without using any inductors. Gyrators can effectively invert impedance.

The impedances (*Z*) (effective resistance) of a capacitor (Z_C) and inductor (Z_L) are given by the well-known formulae:

$$Z_C = \frac{1}{2\pi fC} \text{ and } Z_L = 2\pi fL$$

where *f* is frequency in hertz. An ideal gyrator converts a capacitor of impedance Z_C to $S/Z_C = 2\pi fSC$, where *S* is a scaling factor. Comparing the above equations shows that the converted capacitor behaves like an inductor with value *SC*.

This means that *RL* and *RLC* filter circuits can be created without using inductors. Furthermore, as the effective inductance value depends on resistances in the gyrator circuit, the effective inductance can be changed by varying a resistor – which means that it is reasonably easy to make the circuits tuneable using a variable resistor, such as a potentiometer.

Using a gyrator with a capacitor to create inductance has a number of potential advantages. Where large inductors are required the total weight, size and cost of a gyrator-based implementation can be much lower. Real inductors tend to be less ideal and suffer from more problems than real capacitors, so converting a good quality capacitor to an inductor may give good performance despite the need for additional circuity.

Areas where gyrator-based inductors may help avoid potential problems inherent with wound inductors include influence of magnetic fields, self-resonance due to inter-winding capacitance and core saturation, and power dissipation if DC is applied. Gyrator-based inductors are not suitable for use in circuits such as power converters which rely heavily on the energy storage properties of inductors.

Defining the gyrator

The formal definition of a gyrator is based on the concept of a two-port network – a device with two pairs of terminals (as shown in Fig.1) with a specific relationship between the currents and voltages at the two ports. A well know example of this is the transformer, for which (with an AC signal) $v_2 = Nv_1$ and $i_2 = i_1/N$, where *N* is the turns ratio. The transformer converts an input (primary or port 1) voltage to an output (secondary or port 2) voltage scaled by *N*. Similarly, the primary current is converted to a secondary current. The gyrator is like a variant of the transformer which converts input *voltage* to output *current*, also with a scaling factor, which is called the gyration resistance (*R*). Similarly, the input current is converted to an output voltage. Specifically, the relationships (with reference to Fig.1) are:

$$v_2 = Ri_1 \text{ or } i_1 = v_2/R$$

$$i_2 = -v_1/R \text{ or } v_1 = -Ri_2$$

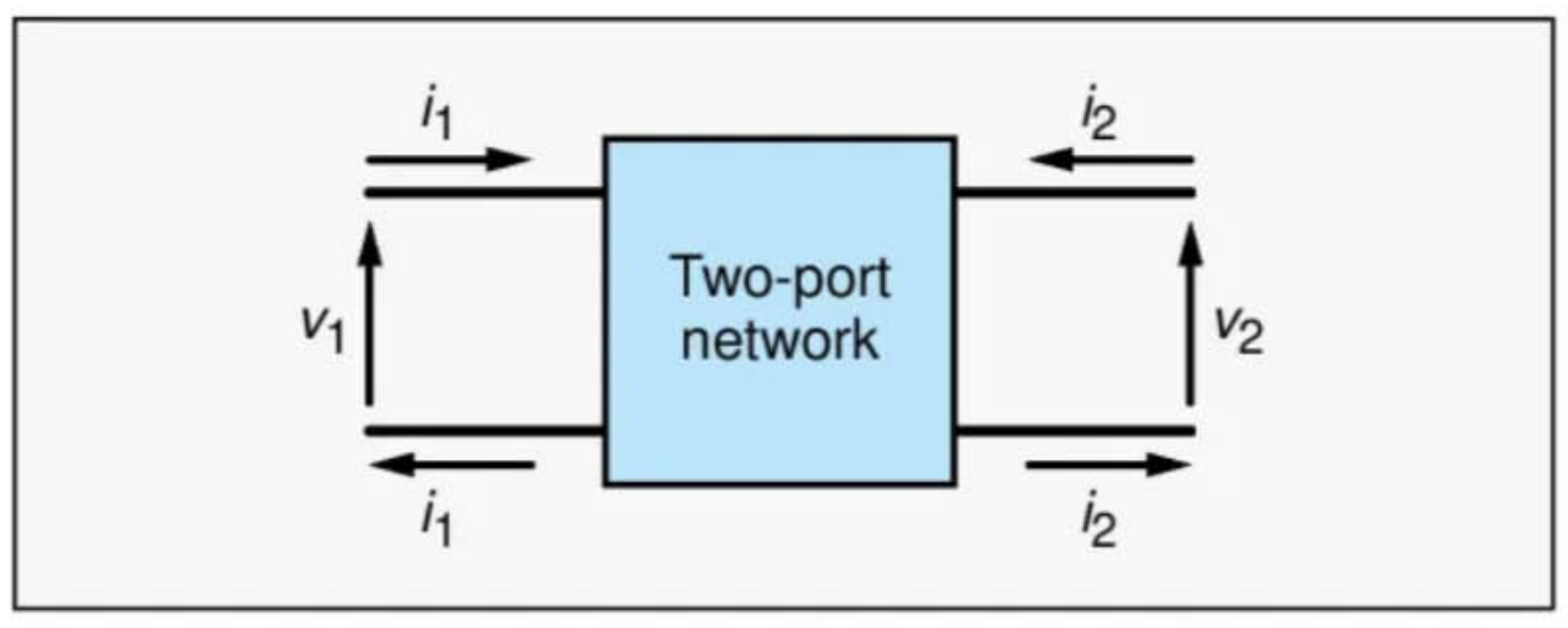


Fig.1. General two port network. Examples include the transformer and gyrator.

The gyrator was proposed by Bernard Tellegen in 1948 in the *Philips Research Reports* journal in a paper titled, *The gyrator, a new electric network element*. This was a largely theoretical paper – there are no relatively simple physical implementations of gyrators as there are with resistors, capacitors, inductors and transformers. Subsequently, however, many gyrator circuits using vacuum tubes, transistors and op amps were developed. To put the date in context, in 1948 the first working transistors had only just been created and tube op amps had only been available for a few years. The name 'gyrator' came from a mathematical analogy between currents and voltages in the gyrator and the mechanical parameters in a gyroscope.

Gyrator with capacitor

Fig.2 shows an ideal gyrator, with gyration resistance *R*, and a capacitor

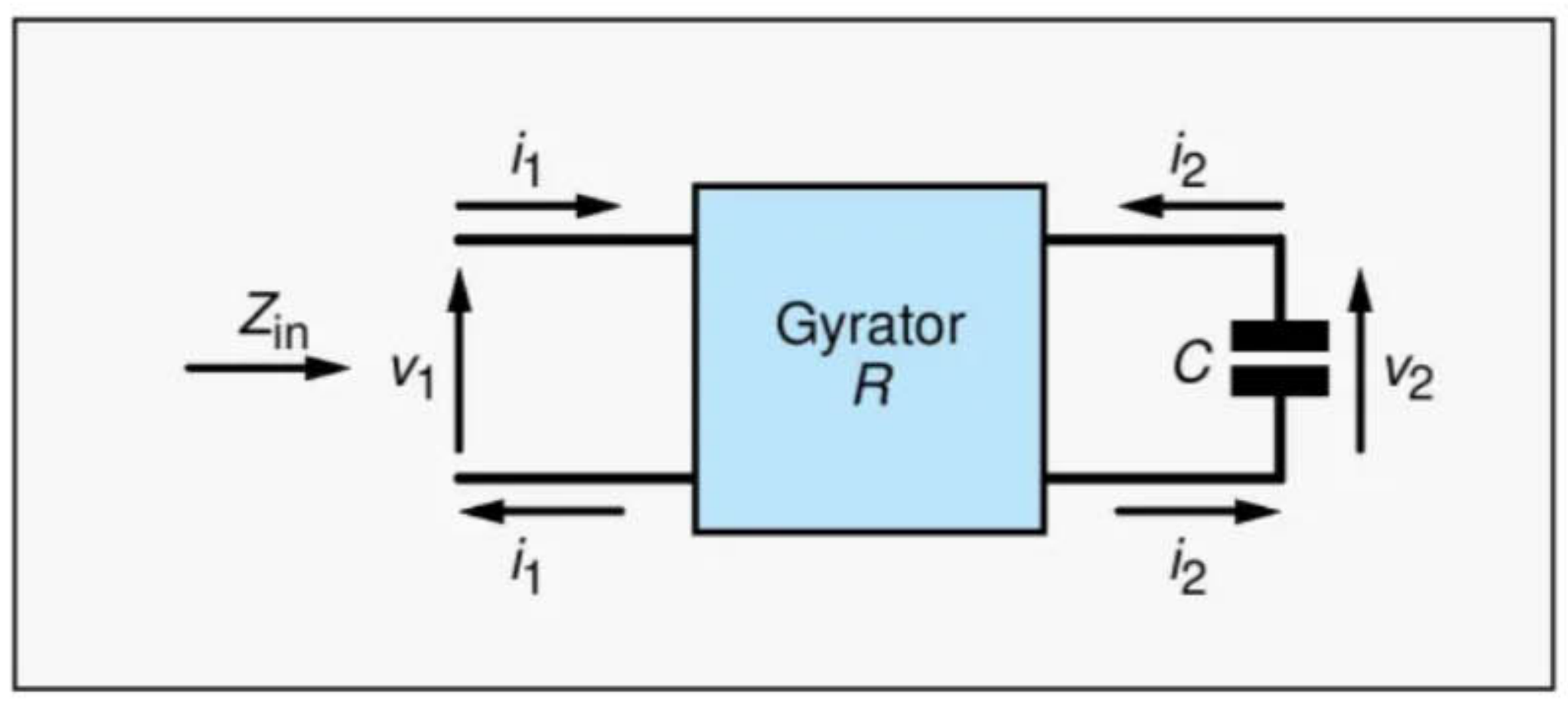


Fig.2. Gyrator with a capacitor on port 2.

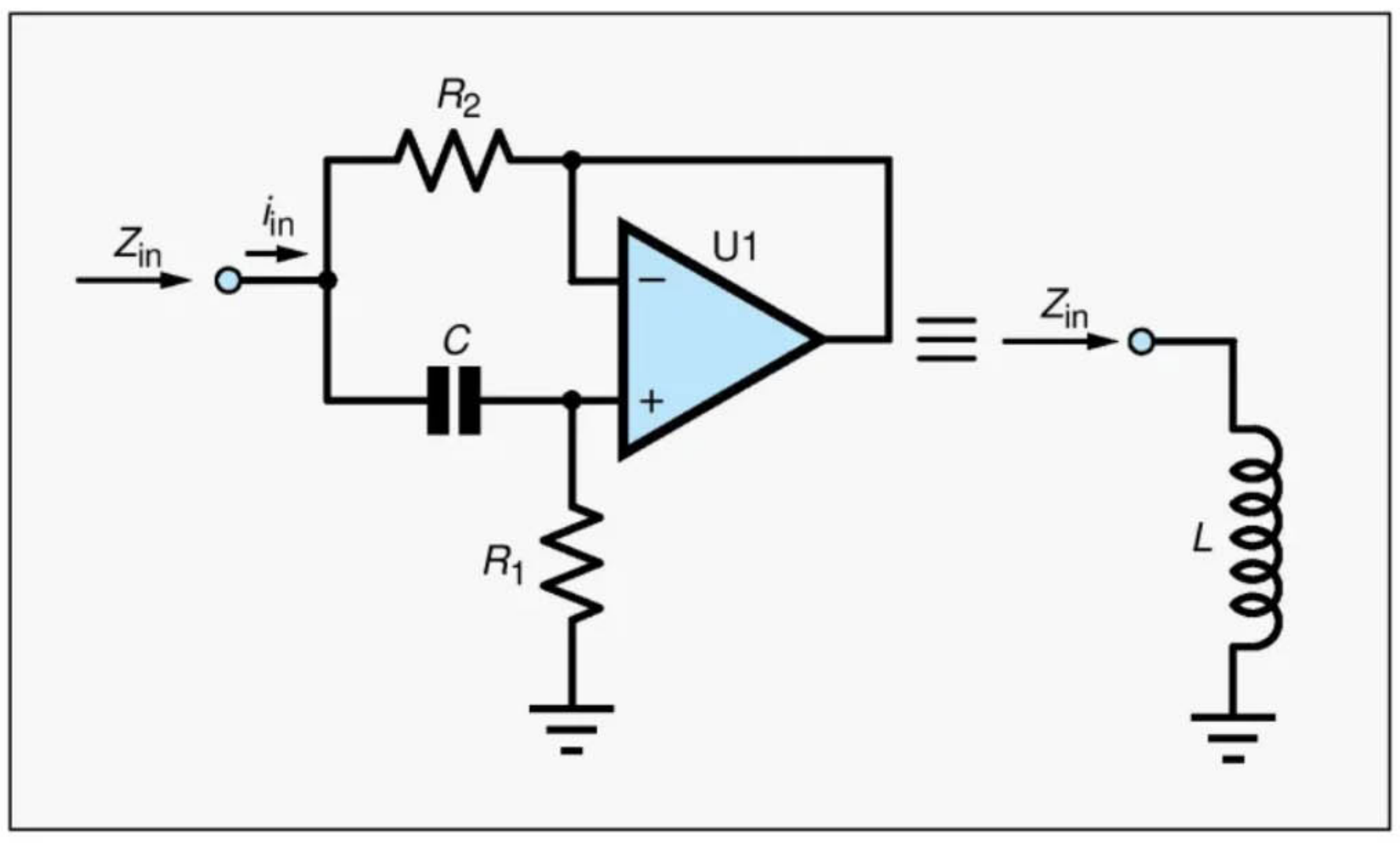


Fig.3. Gyrator circuit to produce behaviour equivalent to an inductor.

(C) on its second port. We can show that port 1 behaves like an inductor.

At port 2 the current and voltage are related by the capacitor's reactance:

$$i_2 = -\frac{v_2}{X_C}$$

Substituting this for i_2 in the gyrator equation $v_1 = -Ri_2$ we get:

$$v_1 = \frac{Rv_2}{X_C}$$

Substituting the other gyrator equation $v_2 = Ri_1$ for v_2, the above gives:

$$v_1 = \frac{RRi_1}{X_C}$$

Dividing by i_1 gives the impedance looking into port 1 (Z_{in}) as:

$$Z_{in} = \frac{v_1}{i_1} = \frac{R^2}{X_C}$$

As discussed above the capacitor's reactance has been inverted. Thus, with a capacitor of value C connected to port 2 of a gyrator with gyration resistance R, port 1 behaves like an inductor with value $L = R^2C$.

Implementing gyrators

There are a variety of transistor and op-amp-based circuits using the gyrator or similar principles to implement behaviour like an inductor. One of the simplest and most popular is shown in Fig.3. It creates an impedance (Z_{in}) to ground that behaves like an inductor. The circuit can be used in place of wound inductors in circuits using grounded inductors.

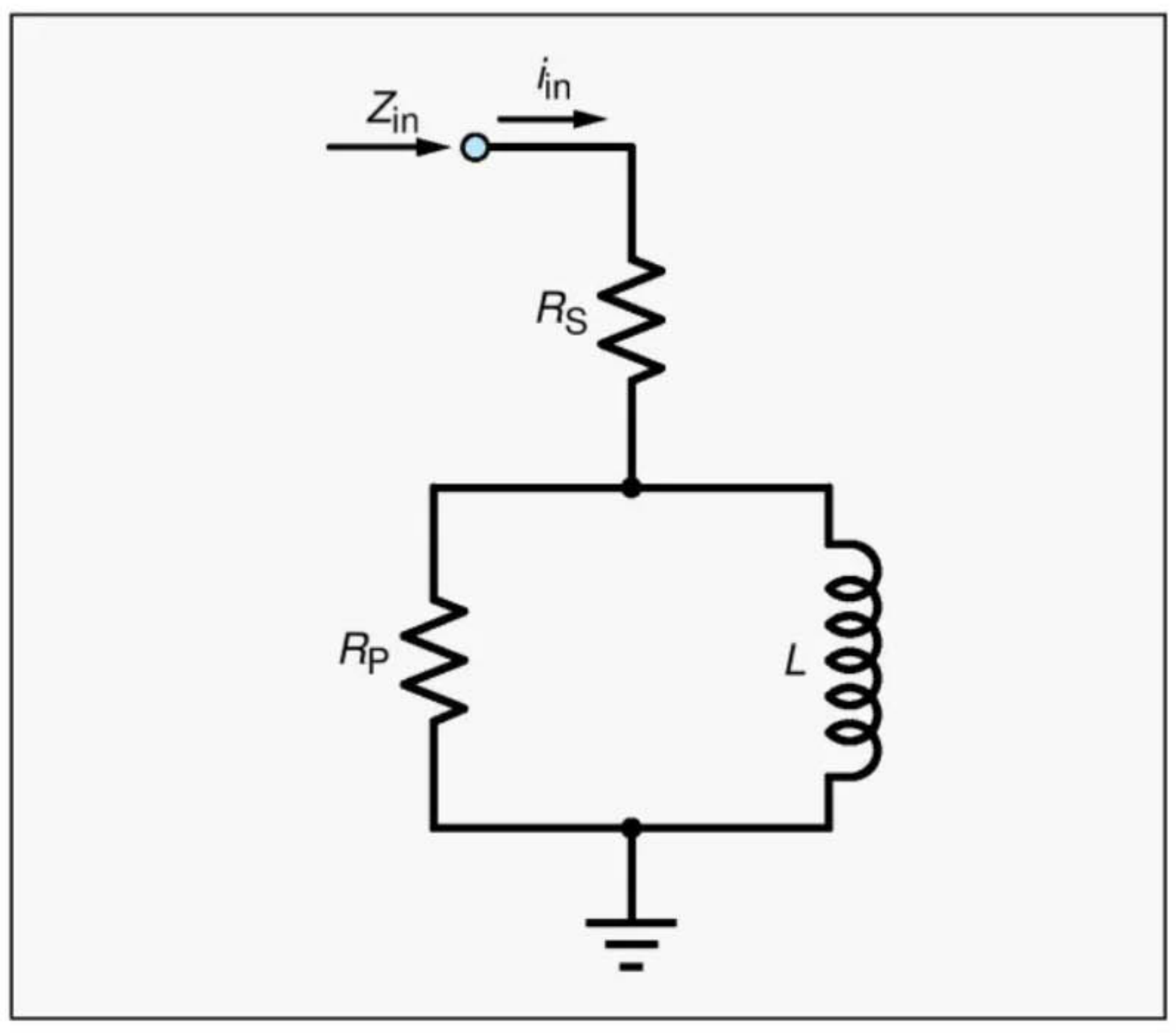


Fig.4. Equivalent circuit for the gyrator in Fig.3.

The circuit in Fig.3 is not particularly easy to understand intuitively, and it does not correspond to the theoretical two-port network gyrator in an obvious way. A brief explanation is as follows. The op amp is configured as a unity-gain buffer. The op amp outputs a voltage equal to that across R_1, which is proportional to the capacitor current (which also flows through R_1). So, the input voltage is forced (via R_2) to be equal to the op amp's output, which is proportional to the capacitor's current. This follows the gyrator behaviour in Fig.2 where the port 1 voltage is proportional to the capacitor (port 2) current. Resistor R_2 is usually relatively small and is effectively in series with the gyrator input (as driven by the op amp) so will appear in series with the effective inductance.

Equivalent circuit

Unlike an ideal gyrator with an ideal capacitor, the circuit in Fig.3 does not behave like an ideal inductor, even if all the components are ideal. An equivalent circuit is shown in Fig.4. This includes both series and parallel resistance, which is similar to what might be expected for a wound inductor. Non-ideal op amps will contribute additional non-ideal characteristics, which we will discuss later.

It is possible to analyse the circuits in Fig.3 and Fig.4 to obtain formulae to relate the values in the two circuits. This requires a lot of algebraic steps, so we outline the process later rather than doing so in minute detail. We will also present simulations which show the equivalence of the two circuits until limited by op amp performance.

With reference to Fig.3 and Fig.4, the gyrator circuit's equivalent inductance value is given by:

$$L = (R_1 - R_2)R_2C$$

Typically, R_1 is relatively large (eg, tens to hundreds of kilohms) and R_2 is relatively small (hundreds of ohms or less) so ($R_1 - R_2$) is not much different from R_1 and a simplified formula can be used:

$$L = R_1R_2C$$

Also, in the equivalent circuit we have:

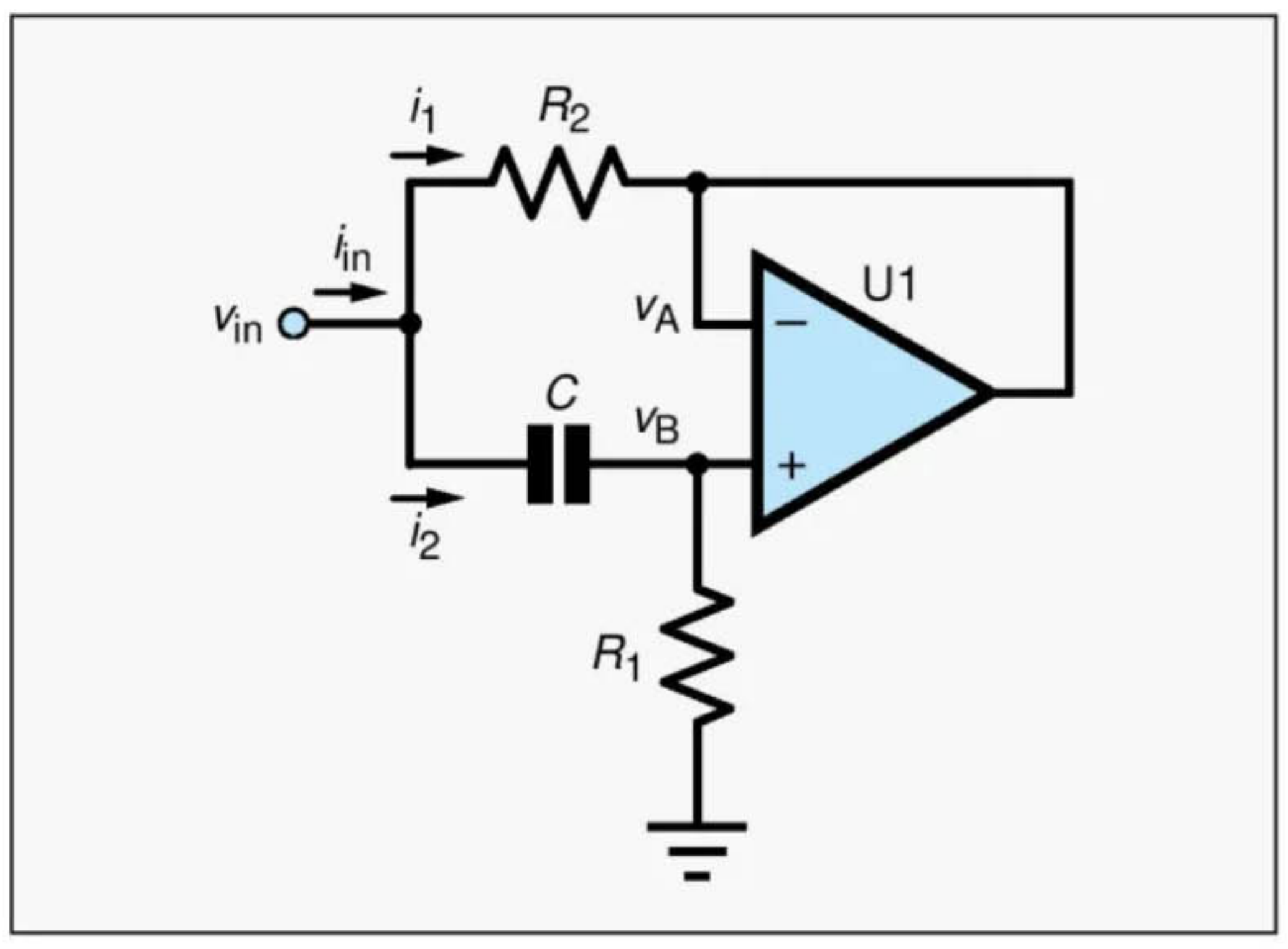


Fig.5. Gyrator analysis

$$R_S = R_2$$
$$R_P = R_1 - R_2$$

With reasonable circuit values it is straightforward to create equivalent inductances of units to tens, or even hundreds of henrys – values which would require large, heavy and expensive windings, or even be unpractical, if implemented as standard wound inductors. For example, with $R_1 = 100\text{k}\Omega$, $R_2 = 100\Omega$ and $C = 200\text{nF}$ then the equivalent inductance is 2.0H.

Circuit analysis

The circuit in Fig.5 is the gyrator from Fig.3 labelled with voltages and currents to facilitate analysis. We have input voltage and current (v_{in} and i_{in}) from which we can find Z_{in} using v_{in}/i_{in}. The op amp's two input voltages are labelled v_A and v_B at the inverting and non-inverting inputs respectively. The op amp's output voltage is also equal to v_A by virtual of the 100% negative feedback connection. Analysis of the circuit is helped by using the assumption that the feedback controls the circuit to maintain zero voltage difference between the two op amp inputs ($v_A = v_B$). This is true for an ideal device and well approximated for a real op amp as long as it is not saturated; that is, if the output voltage is within its linear operating range and is not too close to one of its supply voltages.

The input current splits between the two branches formed by C and R_1 (current i_2) and R_2 (current i_1). Analysis of the circuit is simplified by assuming that no current flows into the op amp inputs. Again, this is true for an ideal device and well approximated by real op amp under normal operating conditions.

For this analysis we will start by using the reactance of the capacitor (its effective resistance) as X_C. A full analysis of the circuit really requires use of the complex number or Laplace domain impedance for the capacitor (see later), but this is sufficient to show the way to proceed without needing the advanced maths. The voltage v_B can be found using the potential divider formula on X_C and R_1, specifically:

$$v_B = \frac{R_1 v_{in}}{R_1 + X_C}$$

Given that i_2 is flowing in R_1, and R_1 has v_B across it, i_2 is v_B/R_1 so we divide the above by R_1 to get:

$$i_2 = \frac{v_{in}}{R_1 + X_C}$$

The voltage across R_2 is $v_{in} - v_A$, which is equal to $v_{in} - v_B$. So, the current in R_2 is $i_1 = (v_{in} - v_B)/R_2$. Using the equation for v_B above we get:

$$i_1 = \left(v_{in} - \frac{R_1 v_{in}}{R_1 + X_C}\right)/R_2$$

To obtain i_{in} we add the two equations for i_1 and i_2 together ($i_{in} = i_1 + i_2$ by Kirchhoff's current law). This give quite a cumbersome expression, which can be simplified by a few algebraic steps: multiplying to obtain equal denominators and cancelling equivalent terms in the resulting numerator:

$$i_{in} = \frac{(R_2 + X_C)v_{in}}{(R_1 + X_C)R_2}$$

From this we obtain Z_{in} as:

$$Z_{in} = \frac{v_{in}}{i_{in}} = \frac{R_2(R_1 + X_C)}{(R_2 + X_C)}$$

As indicated above, R_1 is generally a relatively large value and R_2 is generally relatively small. If R_2 was very small compared to X_C we could ignore R_2 in the denominator. Similarly, if R_1 was very large compared to X_C we could ignore X_C in the numerator. The equation would become R_2R_1/X_C which is an inverted capacitive reactance scaled by R_1R_2 to give effective inductance $L = R_1R_2C$. These approximations will not be true at all frequencies as X_C varies, but this argument helps indicate that the equation makes sense and corresponds with an approximation of the ideal gyrator case discussed above.

Equivalence analysis

To prove that Fig.4 is a valid equivalent circuit for the gyrator inductor we can also find its impedance (Z_{LE}), then equate the two formulae (put $Z_{in} = Z_{LE}$) and compare terms. The impedance of the inductor equivalent circuit is the series sum of resistor R_S plus the parallel combination of resistor R_P and the inductive reactance X_L:

$$Z_{LE} = R_S + \frac{R_P X_L}{R_P + X_L}$$

However, this is not enough – the two equations have to be manipulated into the right equivalent forms in order to be able to relate terms and obtain the results stated earlier, such as:

$$L = (R_1 - R_2)R_2C$$

It is well known that 'resistance' of a capacitor is given by its reactance $X_C = 1/2\pi fC$. However, strictly speaking this is just the magnitude of the impedance at frequency f – it does not account for phase shift. Because capacitors and inductors cause both amplitude and phase shift effects when they are used in a circuit, a single number, 'the resistance', cannot fully account for their behaviour.

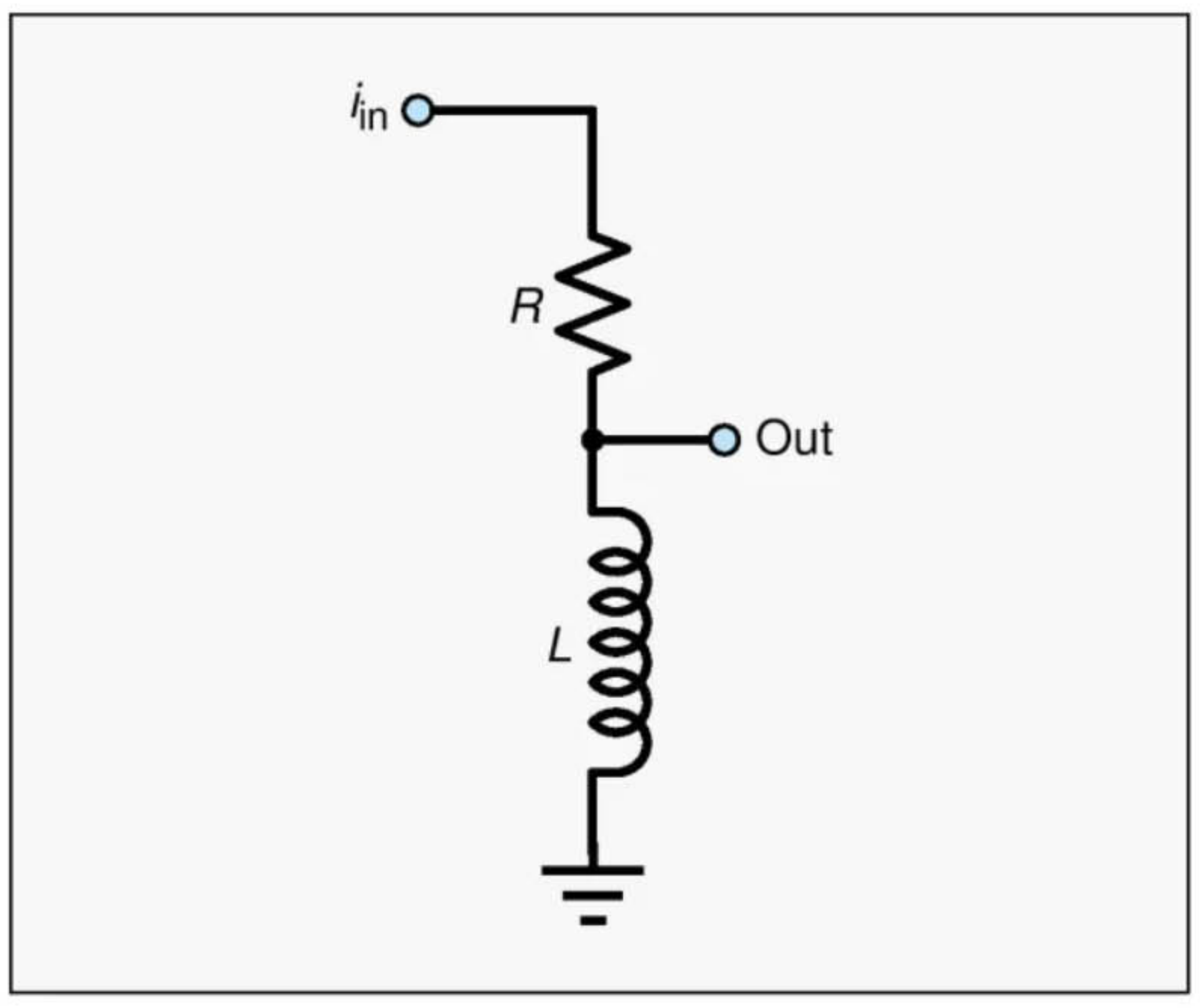


Fig.6. *RL* high-pass filter.

Advanced maths

To overcome this, we use 'complex numbers' to represent impedances in circuits containing inductors or capacitors. Complex numbers are two-part numbers: they have a real part (like standard numbers) plus an imaginary part (standard numbers multiplied by the square root of –1, symbol j). So complex numbers are of the general form $A + jB$. Capacitors have purely imaginary impedance such that $X_C = 1/j\omega C$, where ω is the frequency in radians ($\omega = 2\pi f$ with f in hertz). Using the complex impedance, we can write Z_{in} as:

$$Z_{in} = \frac{R_2(R_1 + 1/j\omega C)}{(R_2 + 1/j\omega C)}$$

This is still not whole story, as such circuits are often analysed in what is called the Laplace domain. This is a mathematical transformation of circuit equations in time to the Laplace domain variable s, which is a complex number related to frequency. In the Laplace domain the impedance of a capacitor is $1/sC$. We can sometimes use $s = j\omega$, which takes us to the complex impedance mentioned above. This is all based on advanced mathematics, but using $X_C = 1/sC$ and $X_L = sL$ you can manipulate the equations using standard circuit theory and standard algebra.

To find the equivalence between the terms in $Z_{in} = Z_{LE}$ we write their formulae in the Laplace domain and wrangle them both into a form where all the s terms are isolated – that is s appears on its own, not multiplied or divided by anything; for example, as in $(s + 1/CR_1)$, not as

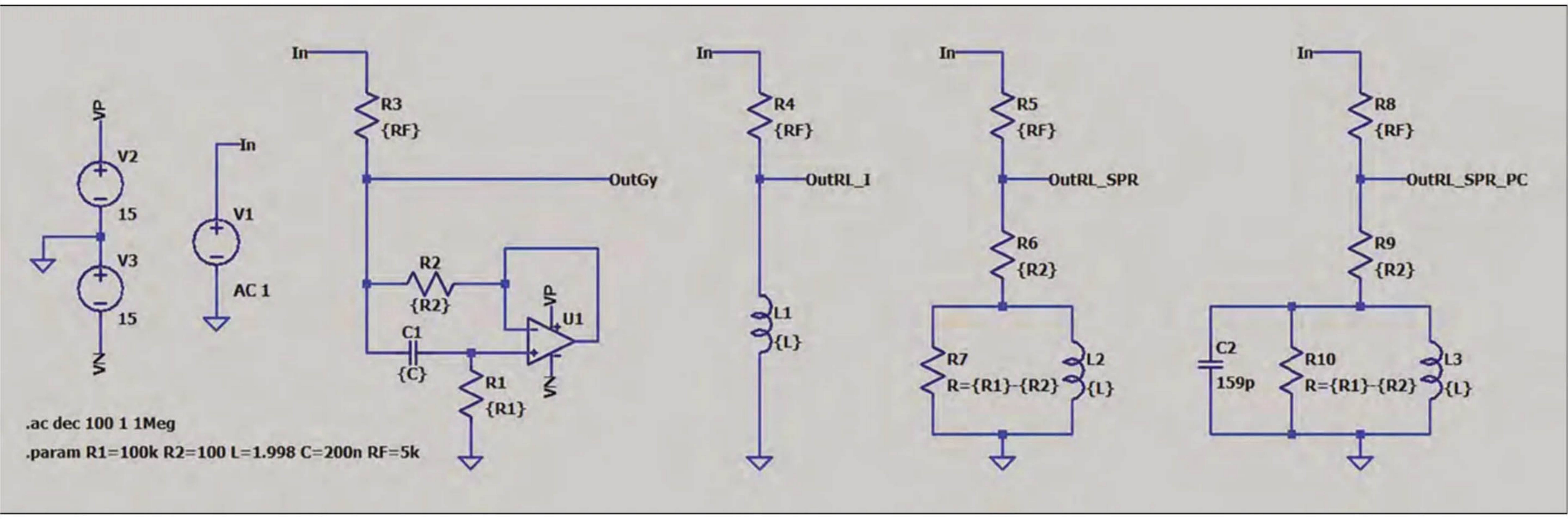


Fig.7. LTspice schematic for simulating a gyrator-based *RL* filter.

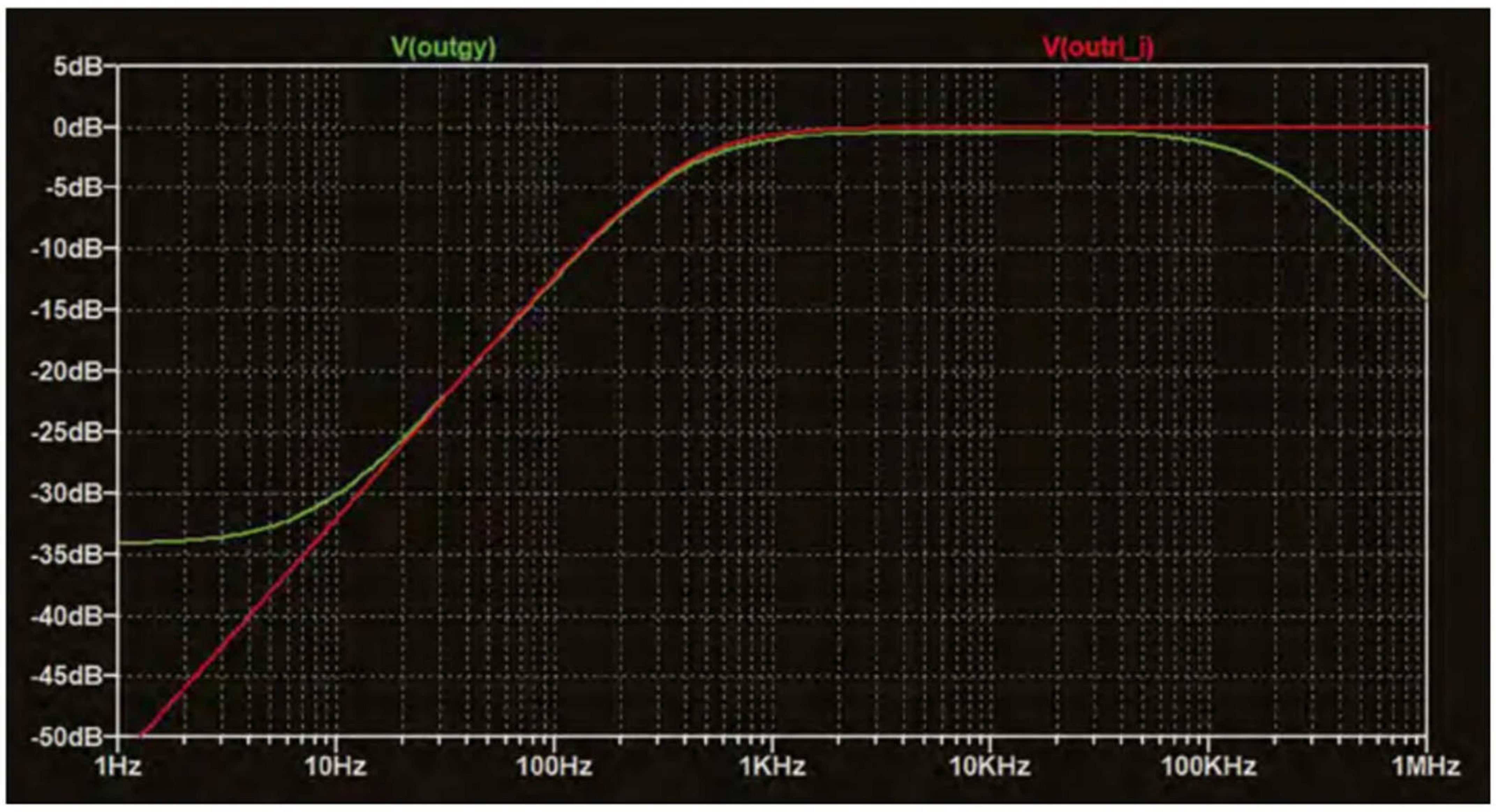


Fig.8. Frequency response of gyrator and ideal inductor-based *RL* filters from Fig.7.

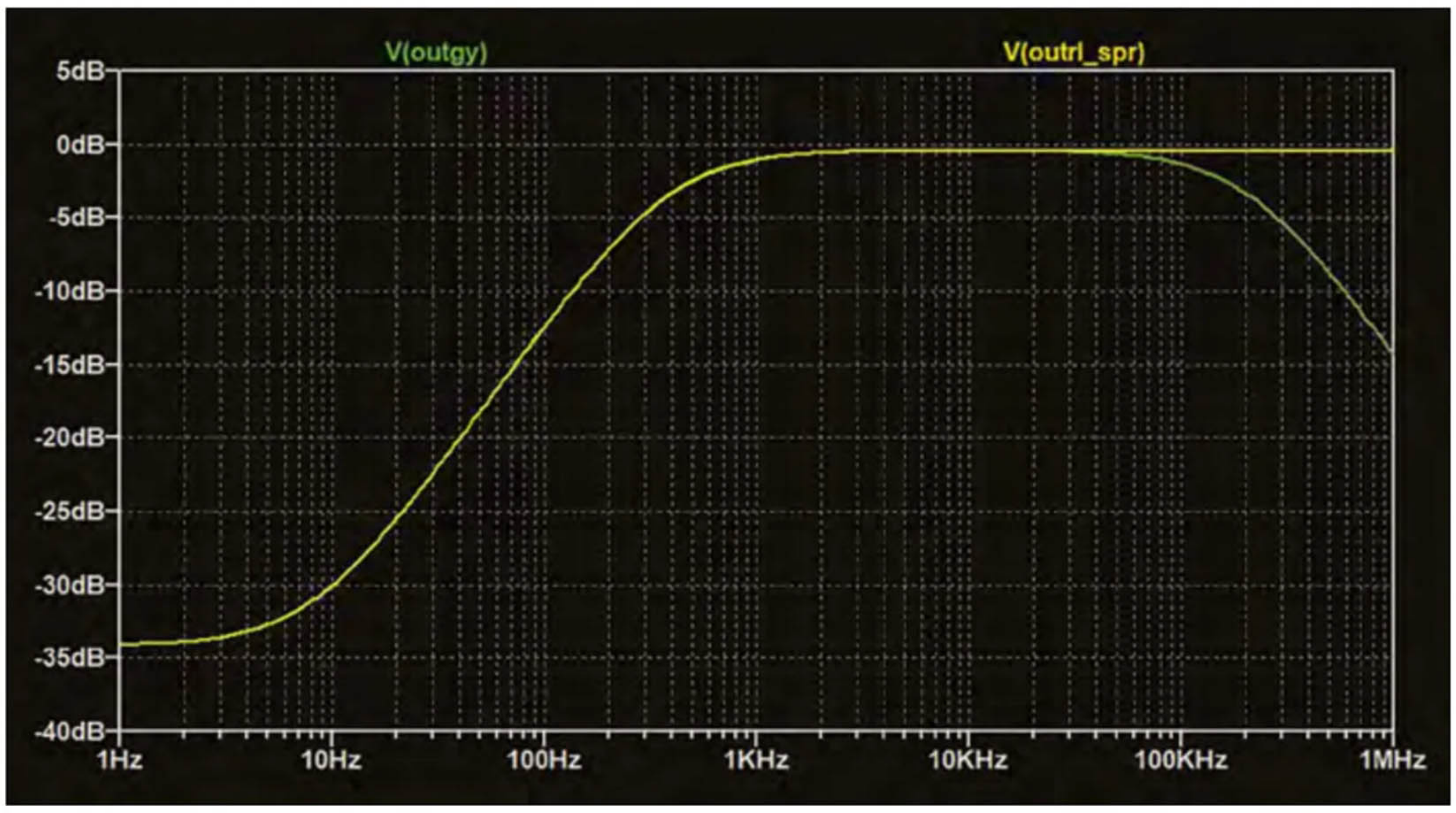
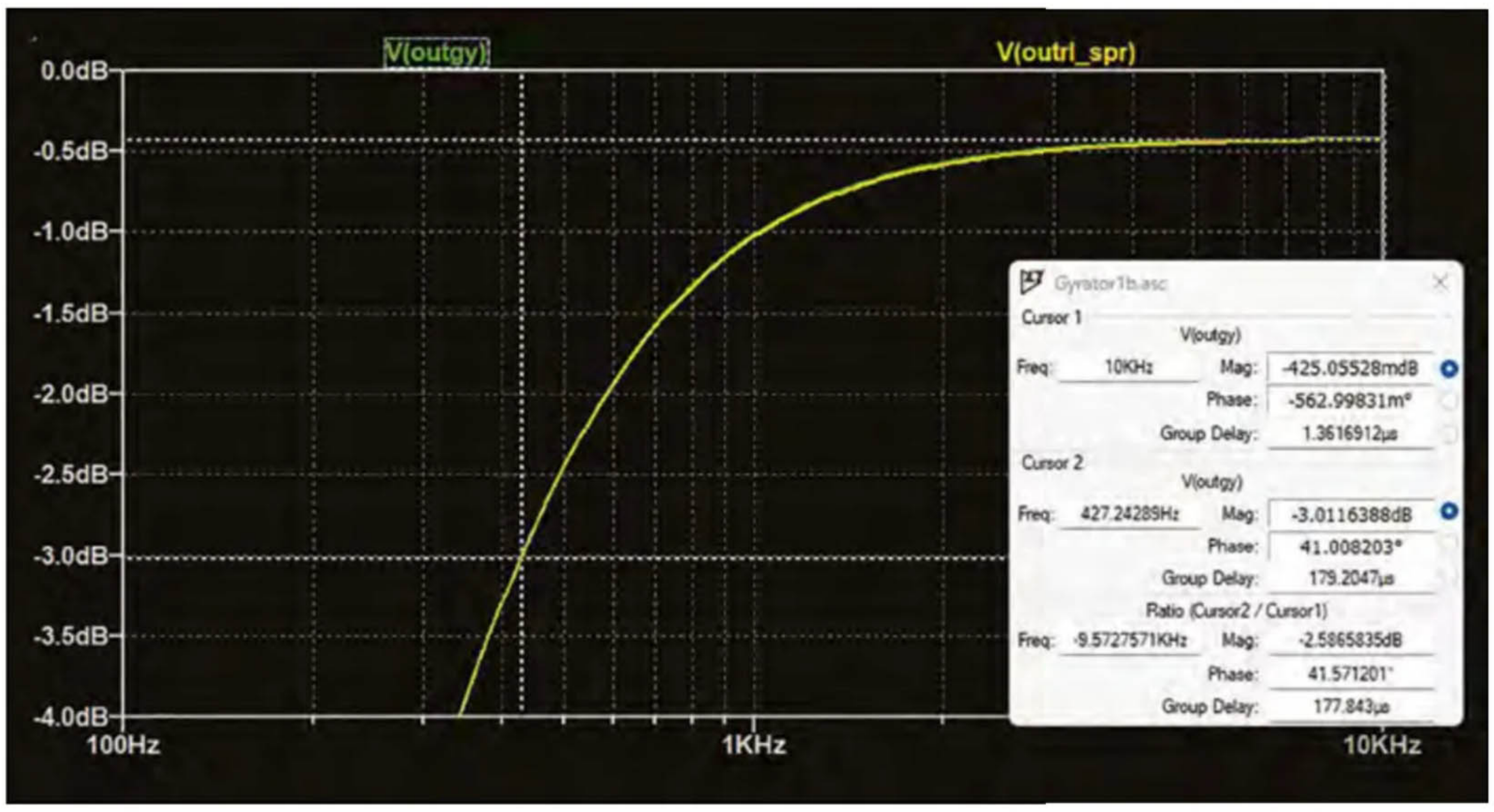


Fig.9. Frequency response of gyrator and equivalent-circuit-based *RL* filters from Fig.7.



Cursor 1
V(outgy)
Freq: 10KHz Mag: -425.05528mdB
Phase: -562.99831m°
Group Delay: 1.3616912µs
Cursor 2
V(outgy)
Freq: 427.24289Hz Mag: -3.0116388dB
Phase: 41.008203°
Group Delay: 179.2047µs
Ratio (Cursor2 / Cursor1)
Freq: -9.5727571KHz Mag: -2.5865835dB
Phase: 41.571201°
Group Delay: 177.843µs

Fig.10. Measuring the cut-off frequency from the response in Fig.9.

in $(1 + sCR_1)$. This takes a few steps for both equations and there is further algebraic manipulation to simplify the comparable terms. Readers interested in the gory details can see every step explained in a video by Old Hack EE here: **https://youtu.be/zpGm4R9eGJk**

Simulation

We can simulate the gyrator circuit in Fig.3 in LTspice, along with some equivalent circuits for comparison, to check how well it implements an inductor. Since gyrators are often used in filters it is appropriate to use the gyrator to implement a simple filter – specifically the first order high-pass *RL* filter shown in Fig.6. This has a grounded inductor, as required by the gyrator implementation. The filter's cut-off frequency is given by the well-known formula $f = R/2\pi L$. Using the example values from above for the gyrator: R_1 = 100kΩ, R_2 = 100Ω, C = 200nF and effective L = 2.0H (more accurately 1.998H). If R = 5.0kΩ then we have a cut-off frequency of 398Hz.

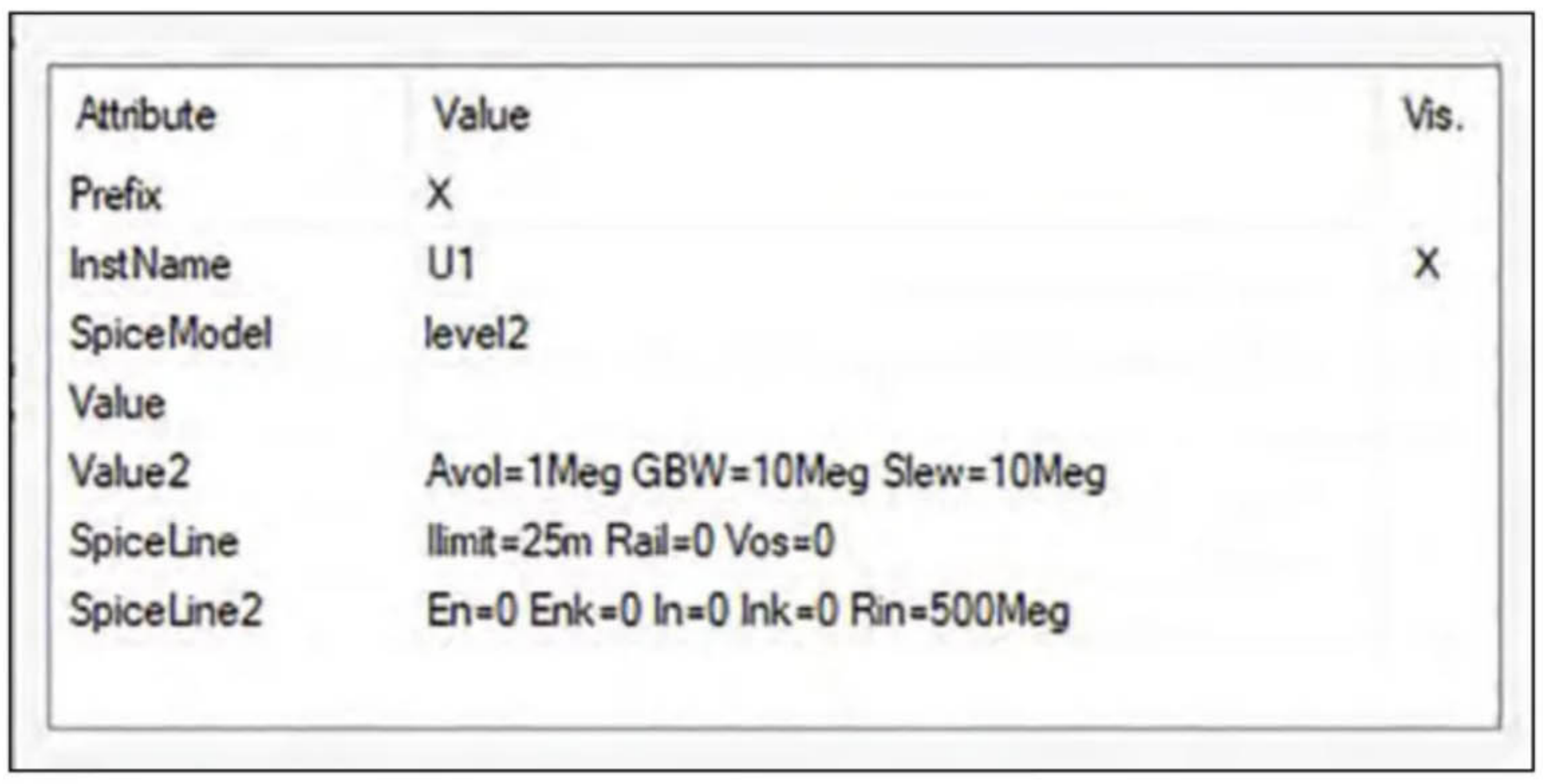
Fig.7 shows an LTspice schematic of the *RL* high-pass filter implemented with the gyrator from Fig.3 (output `OutGy`) and three potentially equivalent *RL* circuits for comparison. This first equivalent uses an ideal inductor (output `OutRL_I`), the second is the equivalent circuit from Fig.4 (output `OutRL_SPR`) and the third is the same as the second with some parallel capacitance added to the inductor. The simulation is configured to perform AC analysis to obtain the frequency response over the range 1Hz to 1MHz. The component values are set using a SPICE `.param` directive. This allows all the components to be updated to new values at once. The parallel resistance value for `R7` and `R10` is set equal to `R1-R2` using behavioural resistors – this is an undocumented LTspice feature which allows resistor formulae to be used, which we have discussed previously.

The gyrator is implemented using an idealised/general op amp model, specifically `UniversalOpamp2` (found at the end of the list of op amps in the component selector). This op amp model has some limitations, such as limited output voltage range, bandwidth and slew rate, which can be changed to investigate their impact on the circuit. The op amp is powered using split ±15V supplies implemented with `V2` and `V3`. Split supplies make it straightforward to handle AC signals and are commonly used with op amps. The input to all the circuits is implemented with `V1`, which is configured for AC analysis at 1V. Using 1V produces plots with correct gain values in dB from the AC analysis.

Results

Some results from simulating Fig.7 are shown in Fig.8, which shows the response of the gyrator and ideal inductor-based versions of the *RL* filter. It can be seen that in the middle of the frequency range, including around the cut-off frequency, the responses match quite closely. At low frequencies the gain of the ideal inductor circuit (red trace) continues to decrease as frequency decreases, whereas the gain of the gyrator-based circuit (green trace) levels off. This is due to the series resistance present in the gyrator circuit.

At low frequencies an inductor is effectively a short circuit, so the circuit becomes a potential divider formed by the frequency-setting resistor (`RF` in Fig.7, *R* in Fig.6) and the inductor series resistor. With a series resistance of 100Ω and *R* in the *RL* filter having a value of



Attribute	Value	Vis.
Prefix	X	
InstName	U1	X
SpiceModel	level2	
Value		
Value2	Avol=1Meg GBW=10Meg Slew=10Meg	
SpiceLine	Ilimit=25m Rail=0 Vos=0	
SpiceLine2	En=0 Enk=0 In=0 Ink=0 Rin=500Meg	

Fig.11. Default parameters for `UniversalOpamp2` in the LTspice Attribute Editor.

5.0kΩ, the potential divider attenuates the signal by a factor of 100/(5000+100) = 0.0196, which is 20log(0.0196) = –34dB. We see the response in Fig.8 levels off at around –34dB at low frequencies.

The gyrator has a series resistance (equal to `R2`), which is included in the second equivalent circuit, that accounts for this behaviour. It is worth noting that wound inductors also have series resistance (winding resistance) which results in similar behaviour to that seen here for the gyrator inductor circuit at low frequencies. Fig.9 shows the simulation of the *RL* filter using the gyrator inductor equivalent circuit from Fig.4 along with the response of gyrator circuit itself. It can be seen that the responses are very close, except at high frequencies. The low-frequency levelling off is very accurate and the matching is also better than for the ideal inductor version in the middle range due to inclusion of the parallel resistance in the inductor equivalent circuit.

Fig.10 shows measurement of the cut-off frequency by zooming in on the response in Fig.9 and using the measurement cursors. The –3dB point is at 427Hz, not 398Hz due to the presence of the series and parallel resistance around the inductor.

Op amp bandwidth

The deviation of the gyrator circuit from the equivalent circuit at high frequencies is not due to a fundamental problem with the equivalent circuit but is due to the limited bandwidth of the op amp used in the simulation. The equivalent circuit assumes an ideal op amp, but the `UniversalOpamp2` in LTspice has finite gain-bandwidth product (GBW) as one of its model parameters. The value of this and other parameters can be set using the attribute editor (see Fig.11), which is accessed by right-clicking the op amp symbol on the schematic. Fig.11 shows the default `UniversalOpamp2` parameters, including `GBW = 10MHz`.

The GBW means that the op amp in the circuit in Fig.7 effectively has a low-pass cut-off frequency of 10MHz. We can model this in the equivalent circuit by adding a capacitor in parallel with the gyrator equivalent inductor. The capacitor should be chosen to give the GBW frequency cut-off in combination with the filter series resistor R_2. That is, we need $1/2\pi R_2C$ = 10MHz, so with R_2 = 100Ω, this gives C = 159pF. At low frequencies this additional capacitor is effectively an open circuit and does not change the response of the equivalent circuit. This effect is similar to that of winding capacitance in wound inductors. Fig.12 shows the simulation of the *RL* filter using the gyrator inductor equivalent circuit with the addition of the parallel capacitor along with the response of the gyrator circuit itself. The two traces now match very closely over the whole frequency range.

We can change the op amp GBW to a higher value to produce a more ideal result. To do this, open the attribute editor (Fig.11) and double-click the text for value 2: `Avol=1Meg GBW=10Meg Slew=10Meg` to enable editing. Change the `GBW` – for example, setting `GBW=100Meg`. Then click OK to close the attribute editor. This results in the response shown in Fig.13. This is for the equivalent circuit without the additional capacitor, and the gyrator circuit (the same signals as in Fig.9). We see that the gyrator circuit matches the equivalent circuit to a much higher frequency. Using general op amp models such as `UniversalOpamp2` provides a straightforward way to explore the effects of op amp characteristics on circuit performance. One parameter can be changed at a time, unlike switching between models of real devices where many characteristics will change.

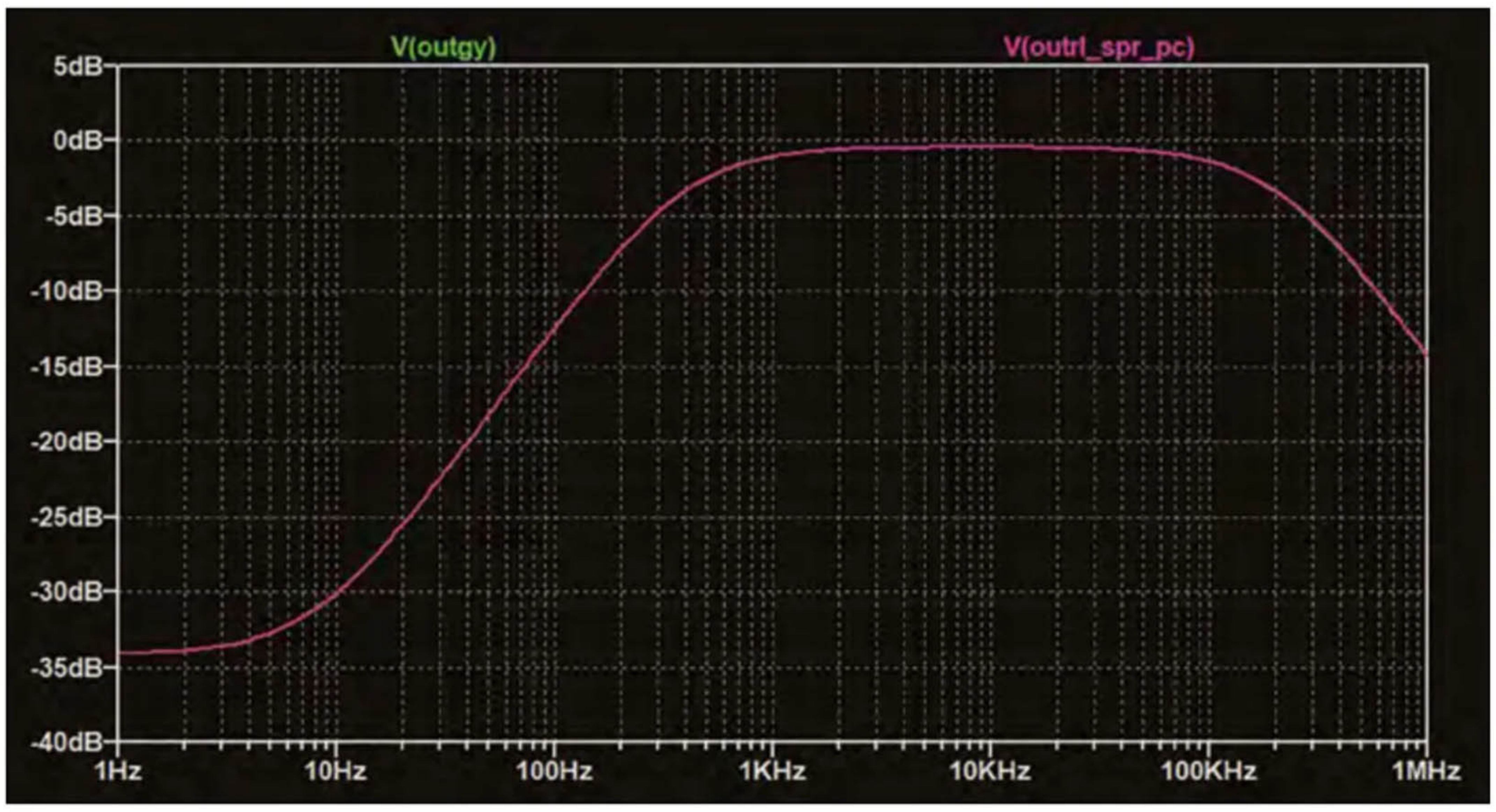


Fig.12. Frequency response of gyrator and equivalent-circuit-based *RL* filters from Fig.7 using the equivalent circuit with the parallel capacitor added to account for op amp GBW.

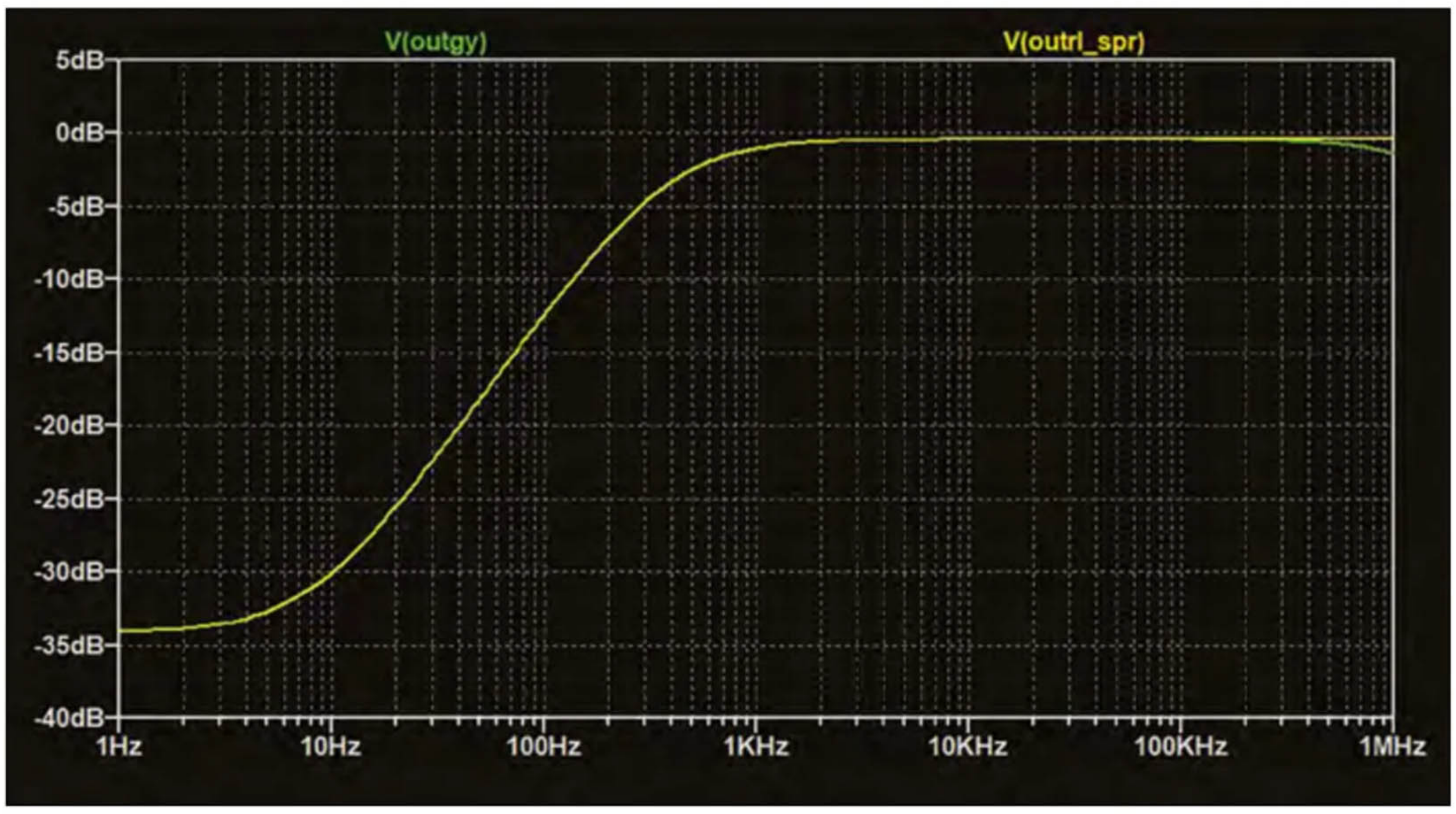


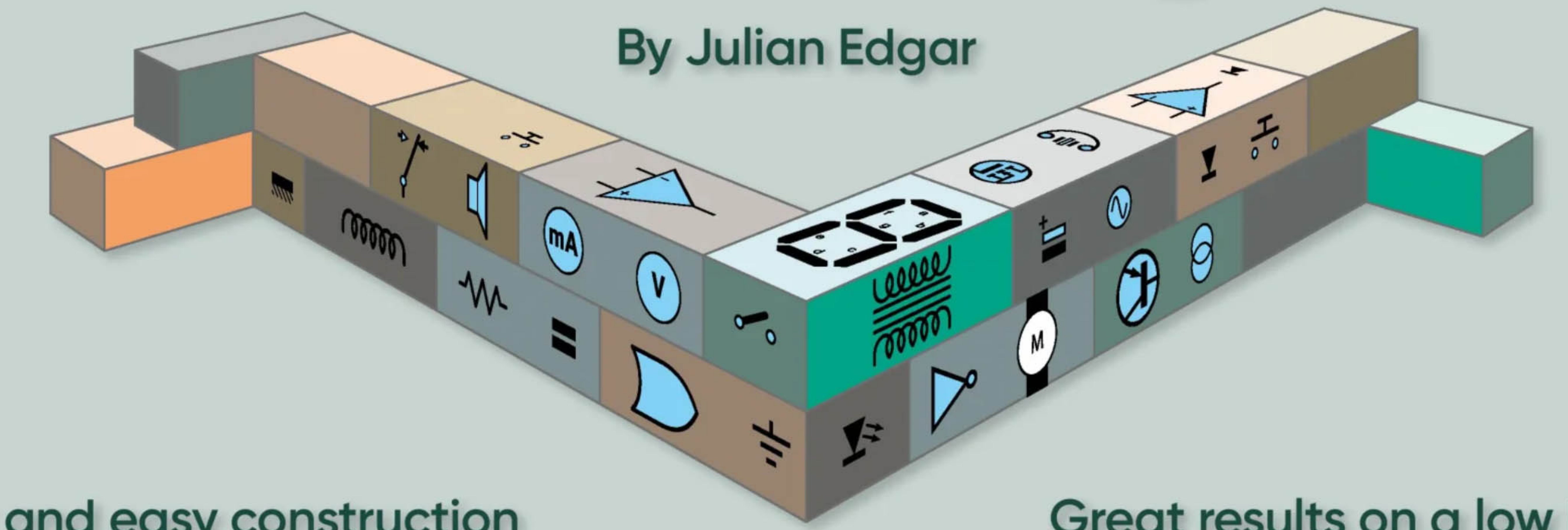
Fig.13. Frequency response of gyrator and equivalent-circuit-based *RL* filters with op amp GBW increased with respect to the circuit used for Fig.9.

Simulation files

Most, but not every month, LTSpice is used to support descriptions and analysis in *Circuit Surgery*.
The examples and files are available for download from the *PE* website.

Electronic Building Blocks

By Julian Edgar



Quick and easy construction

Great results on a low budget

Playing with Bose

Bose gear seems to vary from very good to very bad – so what's there to buy on the second-hand market… and can you make one system sound better?

Bose is a world-famous maker of electronics products, primarily in the field of speakers and amplifiers. They sell professional-level sound reinforcement gear that can be seen in stadia all around the world. And, at the other end of the spectrum, they also sell domestic sound gear.

But say the word 'Bose' to anyone interested in Hi-Fi and they'll likely look rather ill. 'No highs, no lows – that's Bose,' they'll mumble. But I hasten to add (and not just to stop the publisher being sued), I don't agree with that at all.

Decades ago, I remember first hearing a Bose Wave Radio (Fig.1). For such a diminutive thing – well, big for a clock radio, but small for the sound – I was amazed. So amazed in fact that I went away and did some research. It used just two tiny 50mm (2-inch) speakers, but had a very thick enclosure design (a folded waveguide – Fig.2) so clearly a huge amount of electronic equalisation was going on. But hey, I am no purist, and if that's what it took to get such excellent bass, treble, midrange and stereo imaging out of a clock radio – great!

Then I came across some Bose 301 bookshelf speakers (Fig.3), going cheap. I grabbed them, but when I listened, I wasn't much impressed – they just sounded like basic two-way speakers. (Yes, unlike many Bose products, they had tweeters.) But one thing did amaze me – no matter how hard you drove them, they seemed impossible to distort. I opened one up to find, inside, a series lightbulb. Yes, a normal low voltage lightbulb! It acted as a variable resistor: when it got hot, resistance rose and so power was limited. Of course, it probably did all sorts of horrible things to the sound, but oh well…

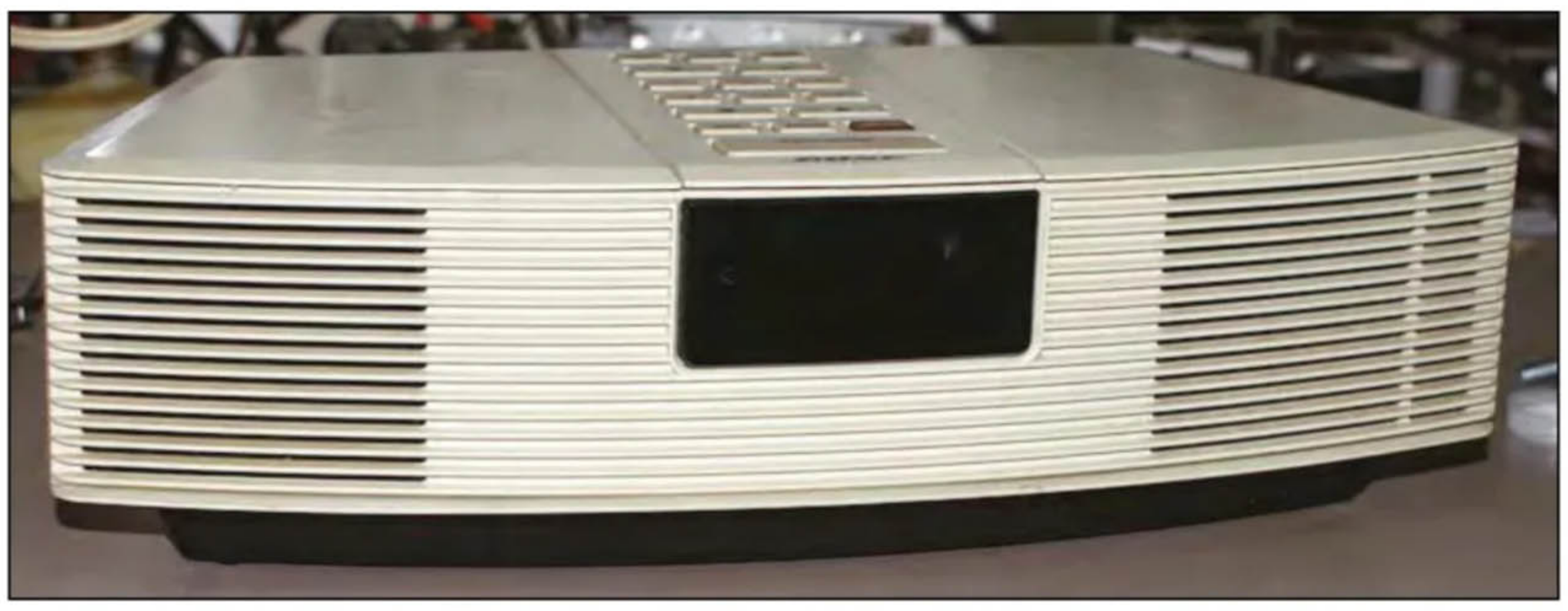


Fig.1. A first-generation Bose Wave Radio – note the vertical grille for the waveguide output (far right). (Courtesy Antique Radio Forums)

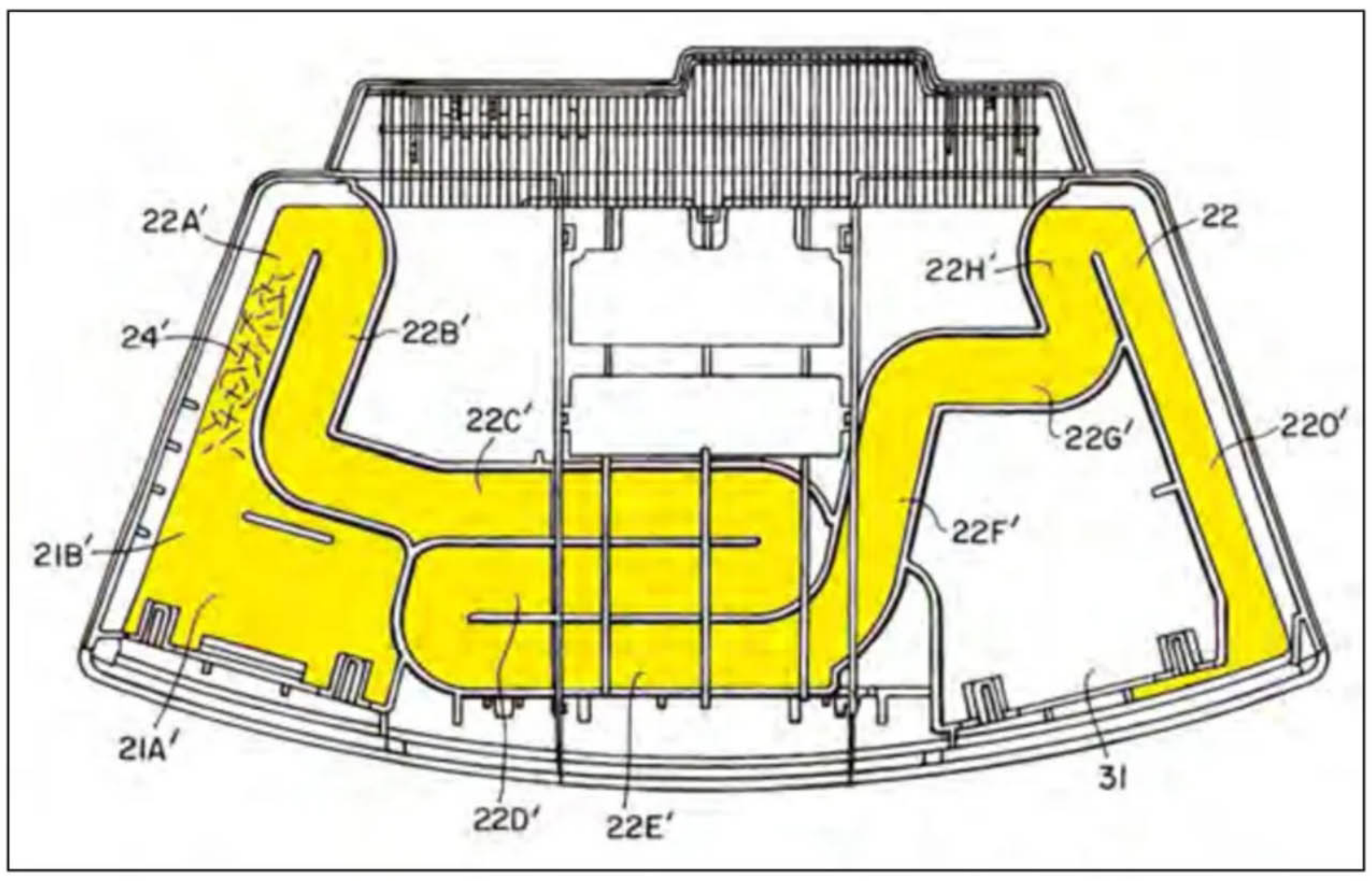


Fig.2. US Patent 6,278,789 for the waveguide in the Bose Wave Radio. Only the speaker on the left acts as a bass driver. (Courtesy US Patents Office)

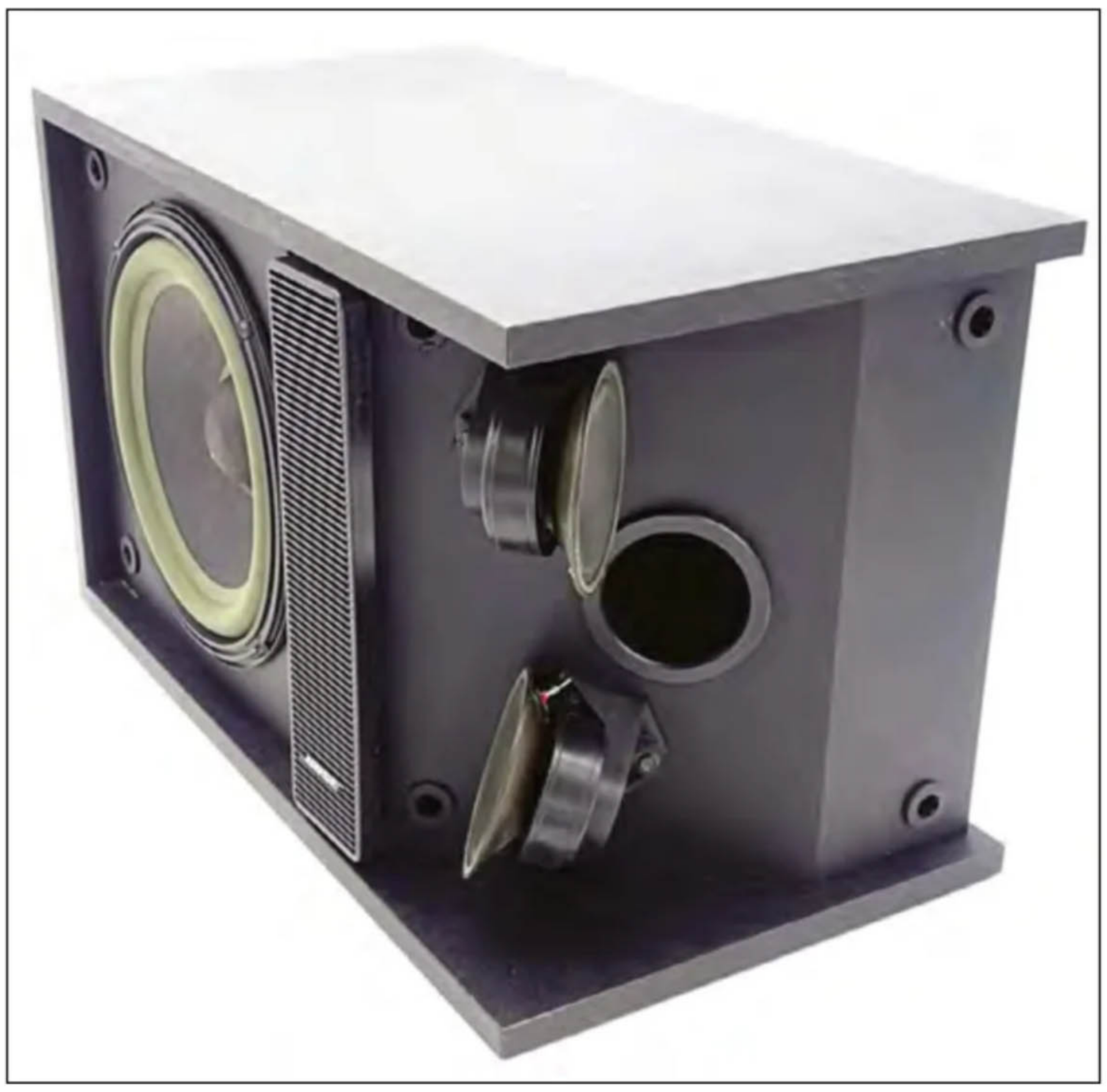


Fig.3. A Bose 301 speaker – open it up and inside you'll find a lightbulb power limiter! I wasn't much impressed with the sound. (Courtesy kulthifi.de)

Fig.4. A Bose 191 in-wall speaker – I gained much better sound from my own homemade in-wall speakers. (Courtesy Bose)

Time passed, then I needed some in-wall speakers. Up popped some Bose 191 speakers (Fig.4) that – yes, you guessed it – I grabbed. But they weren't much good, so I built my own in-wall speakers using Wharfedale drivers and crossovers, salvaged from tower speakers. I kept the internal volume and port size the same as the original Wharfedale enclosures, and they sounded great – much better than the Bose in-wall speakers.

Then – I know, you guessed it – some more Bose stuff crossed my path. But this time it was free – no cost, nothing, nada. (No, I don't know why they were free – the ad appeared on social media; my wife said, 'Do you want these?' I said 'Yes!', and within 30 minutes they were on my desk.)

Bose companion

The product was a Companion 20 multi-media system (Fig.5) – basically, two powered desk speakers for a PC. They're apparently still a current model, retailing at £200. (Like all Bose stuff, very expensive new.). But, like the Wave radio, the acoustic design of these speakers is not at all pedestrian. In this case, a very long folded reflex port is used. And again, I'm sure, a lot of equalisation (ie, bass and treble boost) from the internal amplifier. I think they're outstanding – excellent at low or high volume, good on speech for video conferencing but also good on music and video. And that's what you want with PC speakers. (And no subwoofer needed on the floor.)

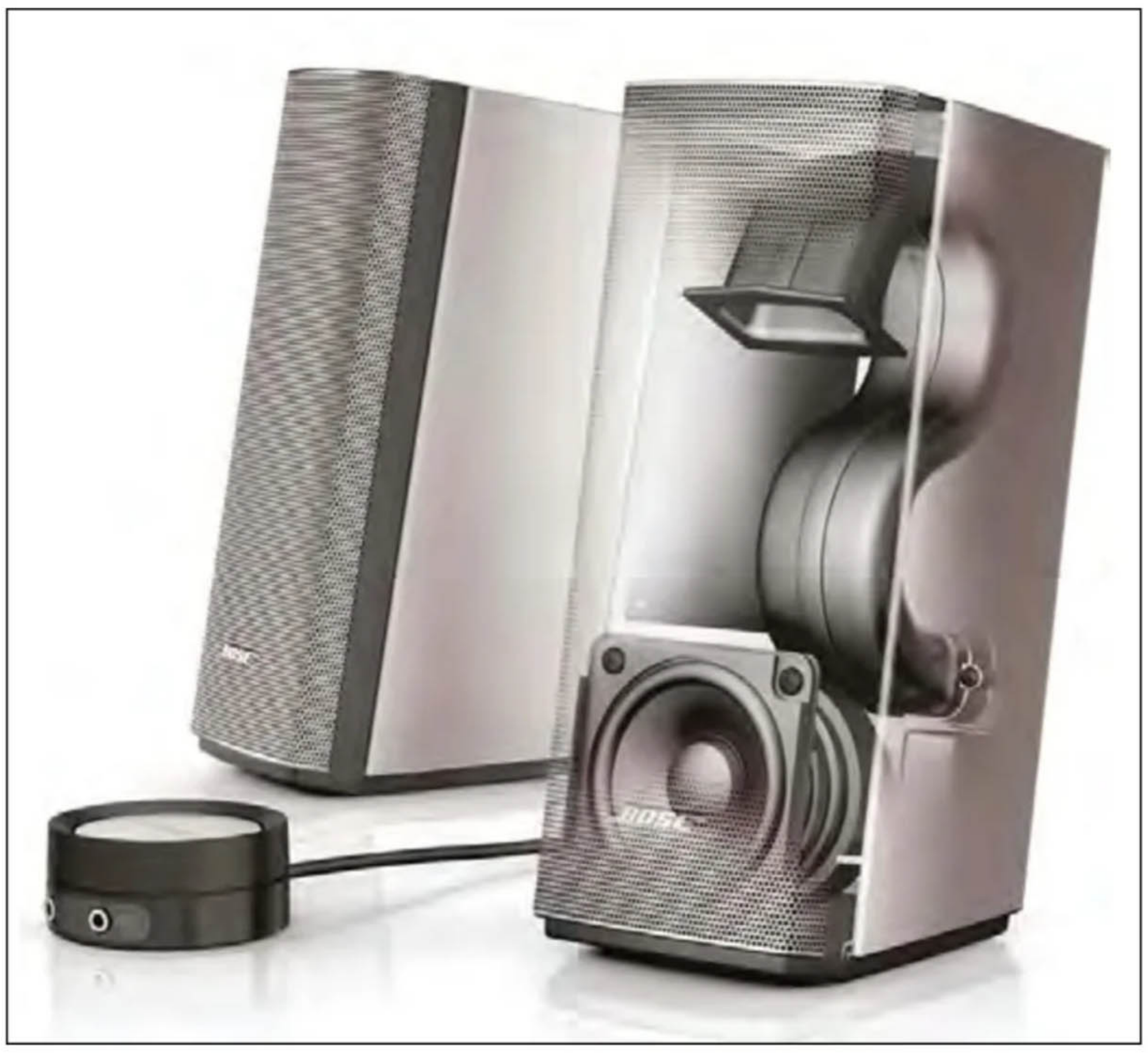


Fig.5. The excellent-quality Bose Companion 20 PC speakers. Note the length of the internal port. (Courtesy Bose)

Hmm, I thought – there seems to be a pattern here. Small Bose stuff is pretty good, larger speakers are not very impressive. (Or what are meant to be larger speakers – more on this in a moment.) So, when a Bose Soundock portable system (Fig.6) was on sale for £5, I bought it. And, as a portable amplified speaker for my phone playing MP3s, it's ideal. Great, room-filling sound from something I can easily carry around and it has its own rechargeable battery.

Bose cubed

Now you might be wondering, where on earth is this going? Well, there's one more step before I get to the nitty gritty. And that's the Bose Lifestyle systems. These comprise very small cube speakers, often with two stacked on top of each other, and a subwoofer module – called by Bose an Acoustimass (see Fig.7). The idea is that you tuck away the cubes, putting them unobtrusively in the corners, for instance, and place the bass module behind a piece of furniture. Then, hey presto, you have a near invisible speaker system! Trouble is, even as long ago as when I first heard the Wave radio, I've never been impressed with the Bose Lifestyle systems. Indistinct, no deep bass – and certainly no treble. The little cubes don't have tweeters – just two full range 50mm (2-inch) speakers. That's it.

The Lifestyle Acoustimass bass modules pop up quite often second-hand, and over the years I have collected three. Some have one bass driver within them, some have two – and some even three. These different configurations are for the different front / rear / surround pairs of speakers that the various Lifestyle systems boast. (You can get Lifestyle systems with anything from two to five dual-cubes.) Basically, the systems use one bass driver per pair of cubes. Some Acoustimass modules have an in-built amplifier but the ones I've got are passive – they need an external amplifier.

Bose has a patent on the acoustic design of some of these bass modules. The driver is buried inside the module, mounted within a partition that divides the interior into two. In parallel with the driver is a port, and then a second, much larger flared port, which connects the interior volumes to the room in which you're listening. (This design is called a bandpass enclosure.) On paper,

Fig.6. My Bose Soundock portable system – great sound and pairs nicely with my phone.

such an enclosure is efficient within only a narrow frequency range – and in practice, my frequency testing shows a decent output from about 40 – 110Hz.

So, if the bass module isn't that bad, what is it about the cubes that lets the Lifestyle systems down? I needed to find out! (I know 40Hz isn't the 20Hz that monster subwoofers can generate, but in the real world, 40Hz isn't terrible for a very small enclosure.)

I kept a lookout for people selling the cubes but weirdly, they don't seem anywhere as numerous as the bass modules (it should be the other way around). Then – and yes, we've finally arrived at the point of this article – I found a system for sale with five black dual-cube speakers and a white bass module. At £25, worth a punt. (And, when I pulled the bass module apart, it even had Bose power-limiting lightbulbs in it!)

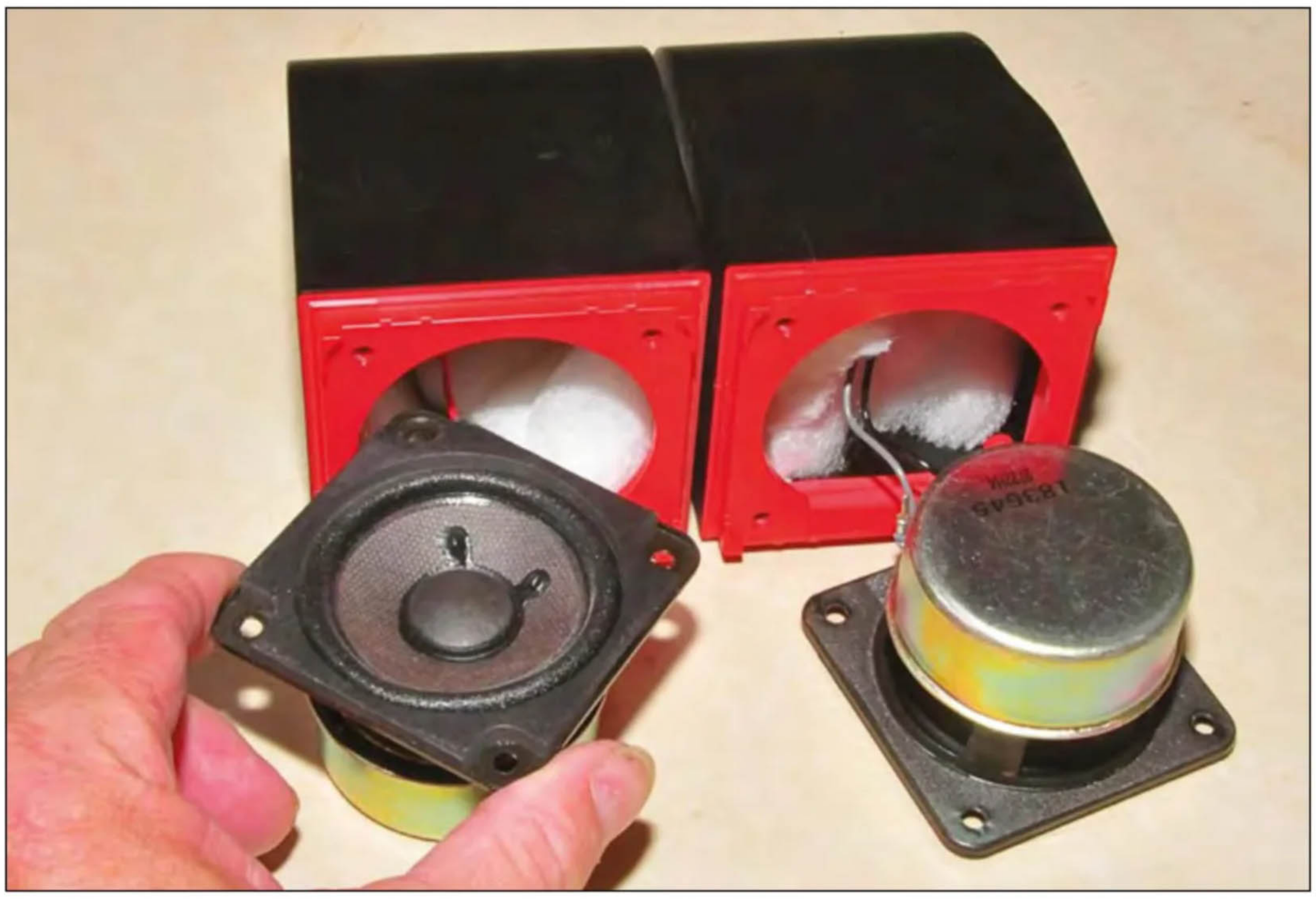


Fig.8. Inside the cubes – one 50mm (2-inch) speaker fot each sealed plastic enclosure stuffed with wadding. There's not a tweeter in sight!

Lifestyle system

And what did it sound like? I'll tell you in a moment, but first a word on the system. The bass module is driven by your chosen amplifier and then the bass module in turn drives the cube speakers. In addition to the power-limiting internal lightbulbs, the bass module has a reasonably complex crossover – I imagine that as well as not feeding bass to the cubes, it also reduces their feed power to better balance their output with the bass module.

I initially had the bass module propped on a chair, the two cubes (I wanted just a stereo system) located each side. And when I played some music? Quite awful. There was no bass, strong but rather metallic mid-range, and zero treble.

So, first things first. The bass module should have been performing better than that, so I acoustically loaded it by placing it on the floor near a wall. For a small system (ie, one that could be hidden), the bass was now reasonable. The midrange (probably the lower midrange) now sounded a little better (although I wasn't entirely convinced) but the treble – still nothing. I ran a frequency generator app through my phone and at 9.5kHz, treble just stopped. I honestly don't remember ever testing a speaker system where treble fell off a cliff at such a low frequency – the same app easily exceeds my limits of hearing on other speakers.

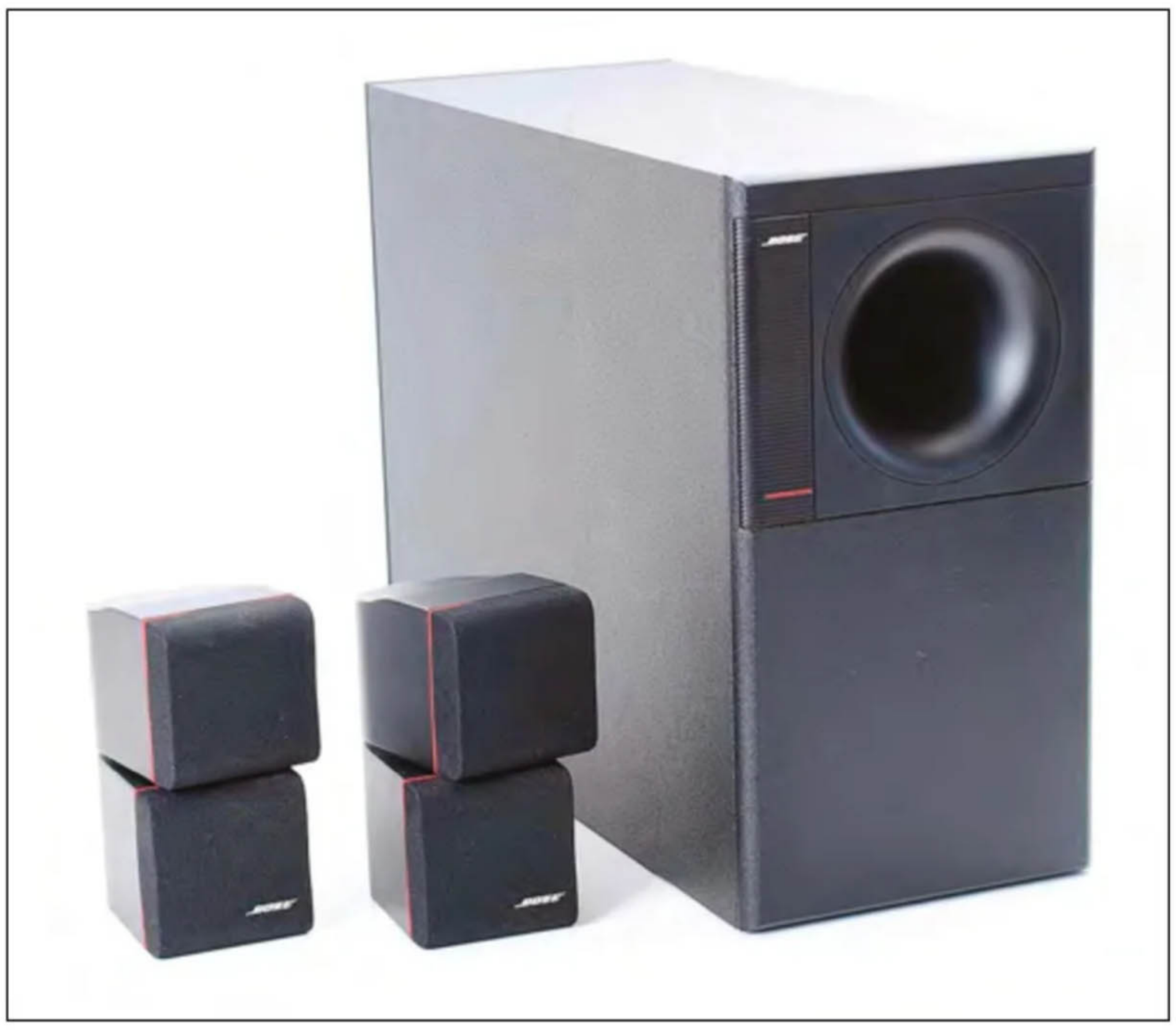


Fig.7. An Acoustimass 5 System – my starting point for modifications. I got what is pictured here plus another three double-cube speakers for £25. 'My' bass model was white.

So, was this a deal-breaker? Well, I was already £25 in, so was it worth spending any more money? Maybe first have a closer look at these world-famous cubes? I opened-up a stacked pair (the grilles can be carefully prised off and then four screws undone to allow each driver to be removed) and looked inside. The 50mm (2in) speakers are identical, with thin foam surrounds, large, shielded magnets and, well, not much else. The voice coil covers are shiny, hard plastic domes (perhaps they're meant to radiate treble?) but there's not a dual cone (a 'whizzer' cone as it used to be called) in sight. And are the enclosures hiding something tricky in their porting? Nope, they're just sealed plastic enclosures filled with wadding; each cube is around 300cm^3 in volume. (Fig.8)

Adding tweeters

Hmmm… how about simply adding some tweeters, each mounted on top of the dual cubes? The price would have to be low, the tweeters would need to suit a ~4Ω system (6Ω measured)

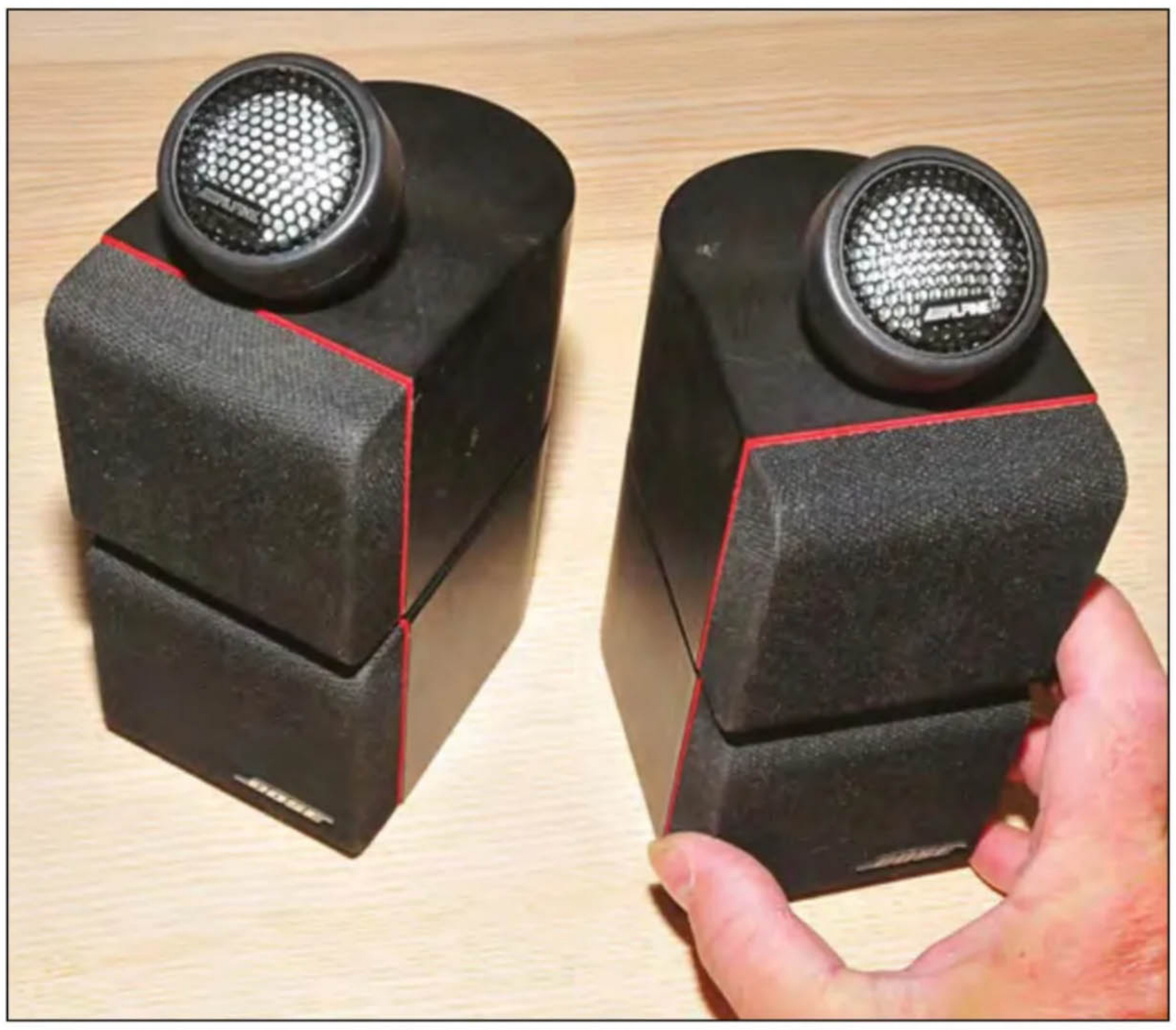


Fig.9. The modified cubes – an Alpine tweeter fitted to each, complete with a 3.3μF capacitor crossover inside. Not visible here is the much smaller mass of fluffy wadding being used in each enclosure. The addition of the tweeters and change in wadding made a major improvement in sound.

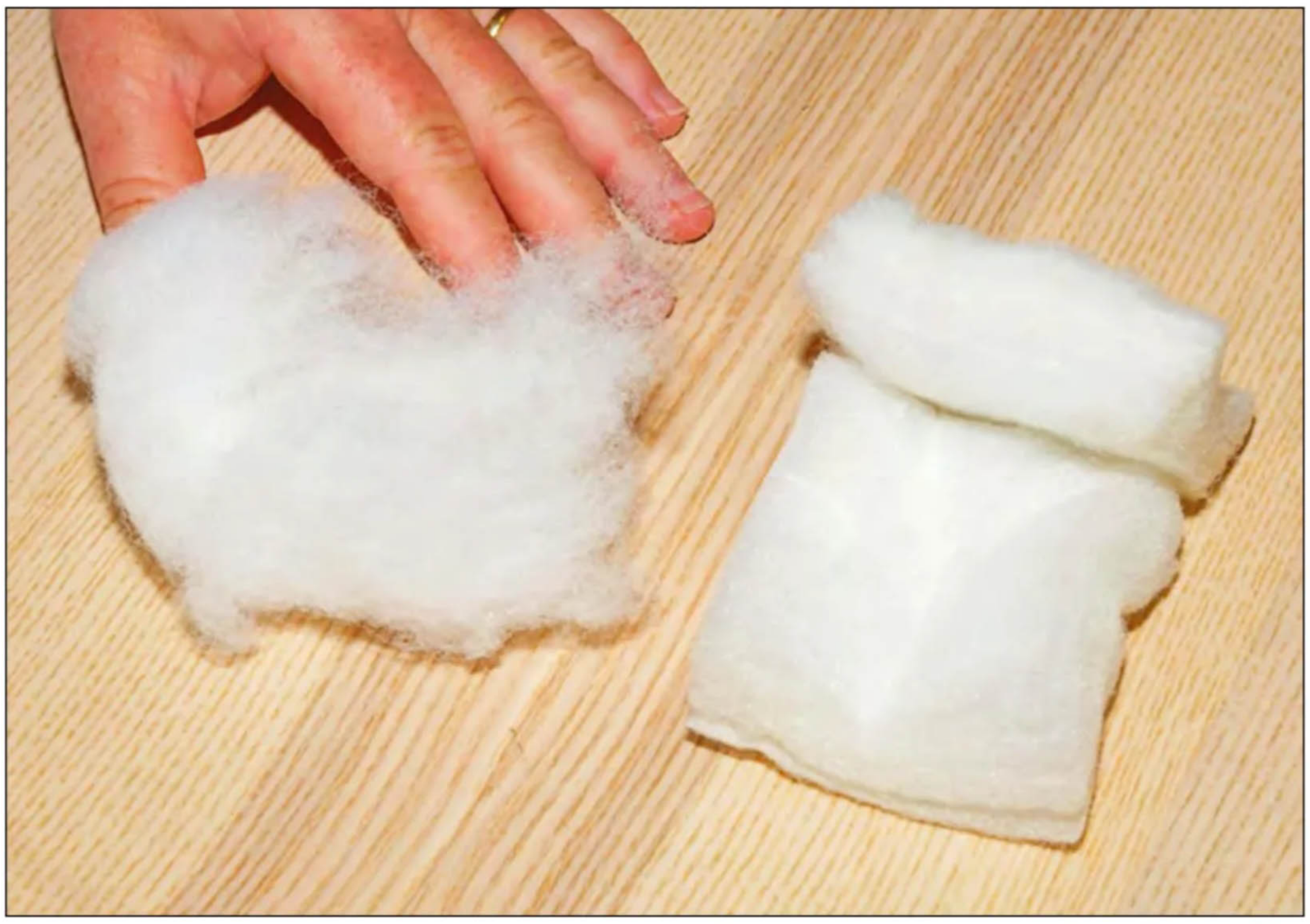


Fig.10. High-density original cube enclosure wadding (right) and new wadding (left).

and they'd need to have their own mounts – and I didn't want to spend very much at all! A quick browse on eBay found just what I wanted – a pair of new Alpine DDT-S30car dome tweeters with crossovers for £12, post included.

The Alpine 'crossovers' ended up being merely 3.3µF capacitors, but all else looked fine. Mounting the tweeters on top of the cubes, drilling a small hole for the wiring and then connecting the tweeters to the internal wiring of the top cube speaker via the supplied capacitor took very little time (Fig.9). So how did they now sound? Vastly better. (Don't let anyone tell you that, just because you're an old geezer, anything above 10,000Hz is irrelevant – it isn't.) The treble was actually now present and the stereo imaging was also now clearer – interesting how much of the 'position' of instruments is carried within the treble frequencies.

But there was a lot still wrong. A frequency test now showed treble well above my ability to hear (you could now hear it fade slowly away as the frequency rose, rather than abruptly stopping as before) but there was a distinct hole in the upper bass. Hmm, what about simply reducing the power to the cubes, while leaving the bass module untouched? I experimented with some series resistors and settled on 10Ω, 10W ceramic resistors in the feeds to the cubes. With the bass module positioned on the floor against a wall, the bass was now over-strong and muddy, but moving the module about 300mm from the wall reduced it nicely.

But now what about the midrange? It wasn't good. I couldn't quite put my finger on it at first, but if anything, it sounded muffled. When I'd previously had the cubes apart, I'd noticed the little enclosures had a lot of rather high density wadding in them – far more than I'd have expected. Was this wadding simply too dense, making the enclosures so dead that any midrange brightness was lost? Time to find out! I opened-up all four enclosures (two cubes in each assembly) and removed the dense wadding, replacing it with the much less dense ex-quilt fluffy wadding that I like to use inside speaker enclosures. (Fig.10) The removed wadding from each cube weighed 10g; the replacement just 2g. So, what was the sound like now? Better – but if anything, the midrange was now a bit too bright! Open up the speakers again, add a little more wadding, and now all was fine. And the final sound – quite acceptable!

I must admit that Bose stuff intrigues me. It is plentiful on the second-hand market, with prices varying from very high to literally giveaway. Would I recommend a used Bose Acoustimass system with cube speakers? Yes, I would – if you want room-filling sound with almost no footprint and you're prepared to make some simple modifications.

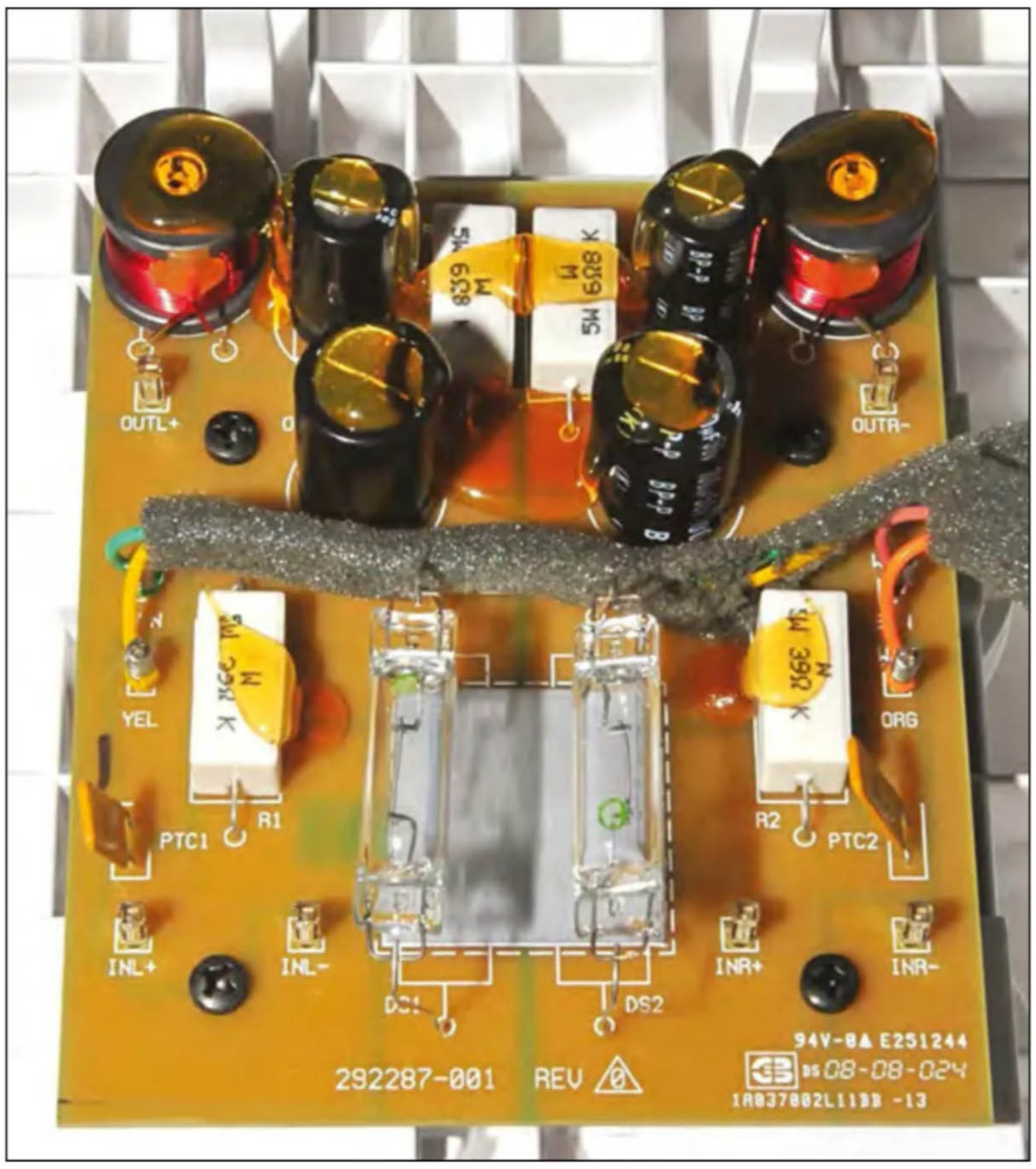


Fig.11. Crossover within the bass module – note the two lightbulb power limiters. An extra two 10Ω, 10W resistors were added in series to the two 'cube speaker' outputs.

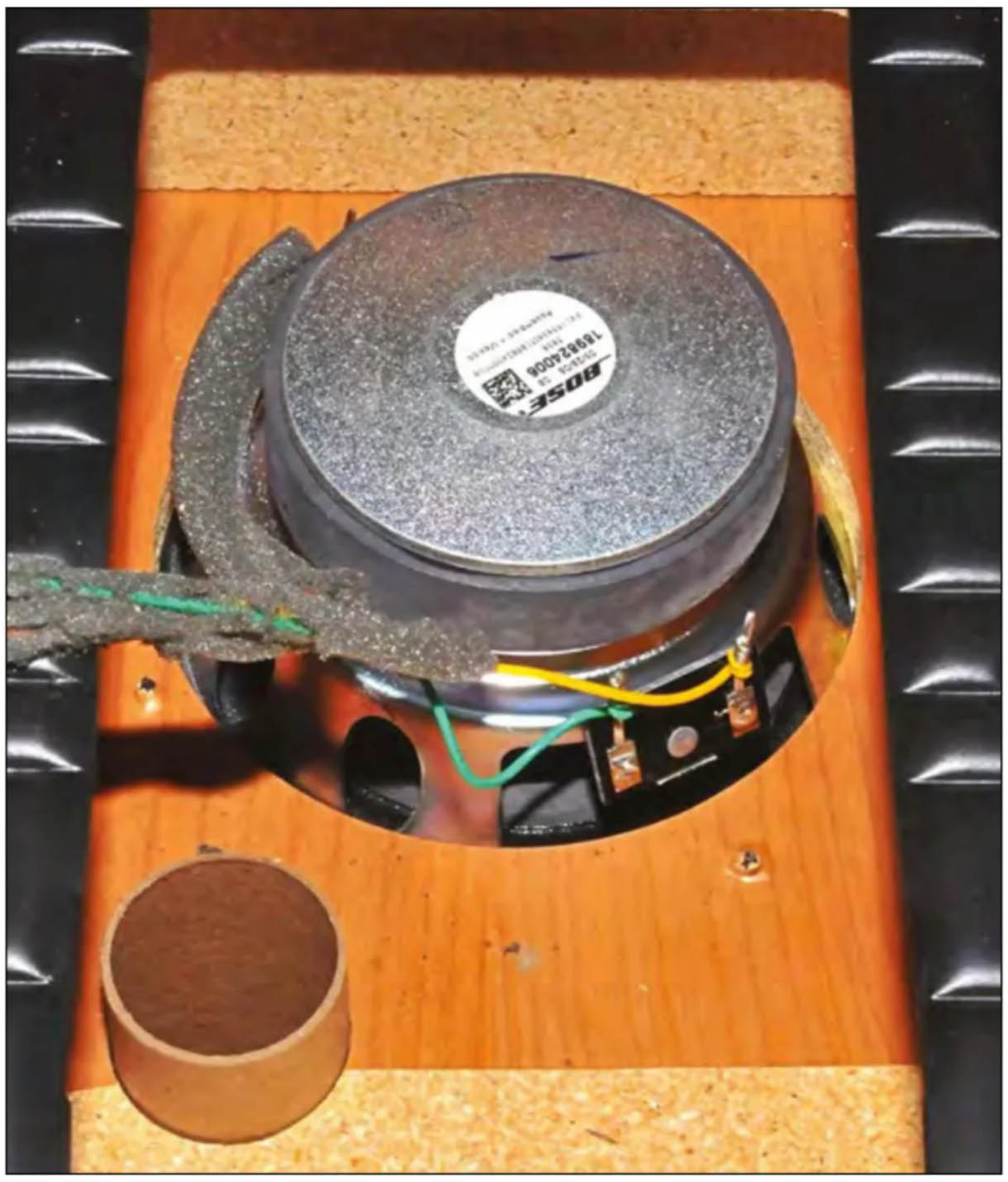


Fig.12. Interior of bandpass bass enclosure – note the port that connects the two internal chambers.

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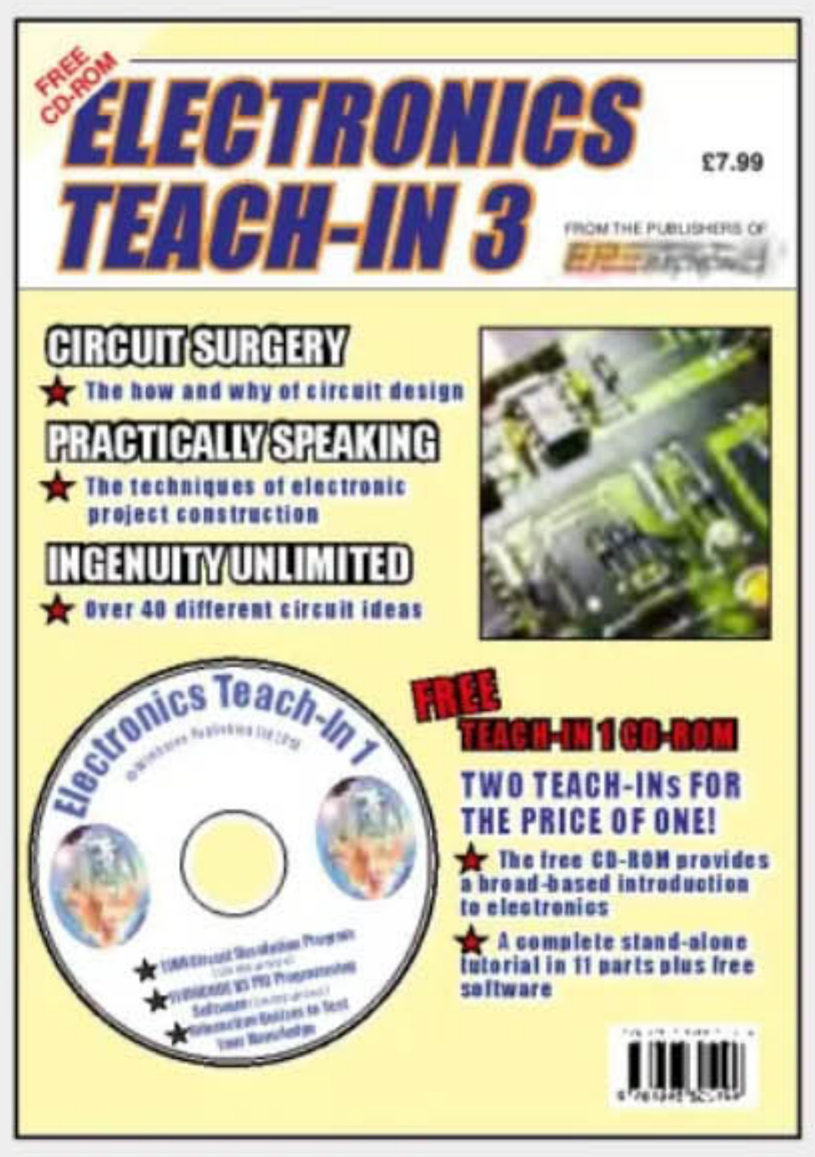

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Teach-In 6 contains an exciting series of articles that provides a complete introduction to the Raspberry Pi, the low cost computer that has taken the education and computing world by storm.

This latest book in our *Teach-In* series will appeal to electronics enthusiasts and computer buffs who want to get to grips with the Raspberry Pi.

Teach-In 6 is for anyone searching for ideas to use their Pi, or who has an idea for a project but doesn't know how to turn it into reality. This book will prove invaluable for anyone fascinated by the revolutionary Pi. It covers:

- ■ Pi programming
- ■ Pi hardware
- ■ Pi communications
- ■ Pi Projects
- ■ Pi Class
- ■ Python Quickstart
- ■ Pi World
- ■ ...and much more!

The *Teach-In 6* CD-ROM also contains all the necessary software for the series, so that readers and circuit designers can get started quickly and easily with the projects and ideas covered.

ELECTRONICS TEACH-IN 6
RASPBERRY Pi

ELECTRONICS TEACH-IN 7 – CD-ROM
DISCRETE LINEAR CIRCUIT DESIGN

Mike & Richard Tooley

Teach-In 7 is a complete introduction to the design of analogue electronic circuits. It is ideal for everyone interested in electronics as a hobby and for those studying technology at schools and colleges. The CD-ROM also contains all the circuit software for the course, plus demo CAD software for use with the *Teach-In* series.

- ■ Discrete Linear Circuit Design
- ■ Understand linear circuit design
- ■ Learn with 'TINA' – modern CAD software
- ■ Design simple, but elegant circuits
- ■ Five projects to build:
  - i) Pre-amp
  - ii) Headphone Amp
  - iii) Tone Control
  - iv) VU-meter
  - v) High Performance Audio Power Amp.

PLUS

Audio Out – an analogue expert's take on specialist circuits

Practically Speaking – the techniques of project building.

ELECTRONICS TEACH-IN 7
DISCRETE LINEAR CIRCUIT DESIGN

ELECTRONICS TEACH-IN 8 – CD-ROM
INTRODUCING THE ARDUINO

Mike & Richard Tooley

Hardware: learn about components and circuits
Programming: powerful integrated development system
Microcontrollers: understand control operations
Communications: connect to PCs and other Arduinos.

Teach-In 8 is an exciting series designed for electronics enthusiasts who want to get to grips with the inexpensive, popular Arduino microcontroller, as well as coding enthusiasts who want to explore hardware and interfacing. It will provide a one-stop source of ideas and practical information.

The Arduino offers a truly effective platform for developing a huge variety of projects; from operating a set of Christmas tree lights to remotely controlling a robotic vehicle through wireless or the Internet.

Teach-In 8 is based around a series of practical projects with plenty of information for customisation.

This book also includes *PIC n' Mix*: 'PICs and the PICkit 3 – A Beginners guide' by Mike O'Keefe and *Circuit Surgery* by Ian Bell – 'State Machines part 1 and 2'.

The CD-ROM includes the files for:

- ■ *Teach-In 8*
- ■ Microchip MPLAB IDE XC8 8-bit compiler
- ■ PICkit 3 User Guide
- ■ Lab-Nation Smartscope software.

ELECTRONICS TEACH-IN 8
INTRODUCING THE ARDUINO

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JUNE 2022		
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PCBs for most recent *PE*/*EPE* constructional projects are available. From the July 2013 issue onwards, PCBs with eight-digit codes have silk screen overlays and, where applicable, are double-sided, have plated-through holes, and solder mask. They are similar to photos in the project articles. Earlier PCBs are likely to be more basic and may not include silk screen overlay, be single-sided, lack plated-through holes and solder mask.

Always check price and availability in the latest issue or online. A large number of older boards are listed for ordering on our website.

In most cases we do not supply kits or components for our projects. For older projects it is important to check the availability of all components before purchasing PCBs.

Back issues of articles are available – see Back Issues page for details.

Double-sided | plated-through holes | solder mask

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JANUARY 2021		
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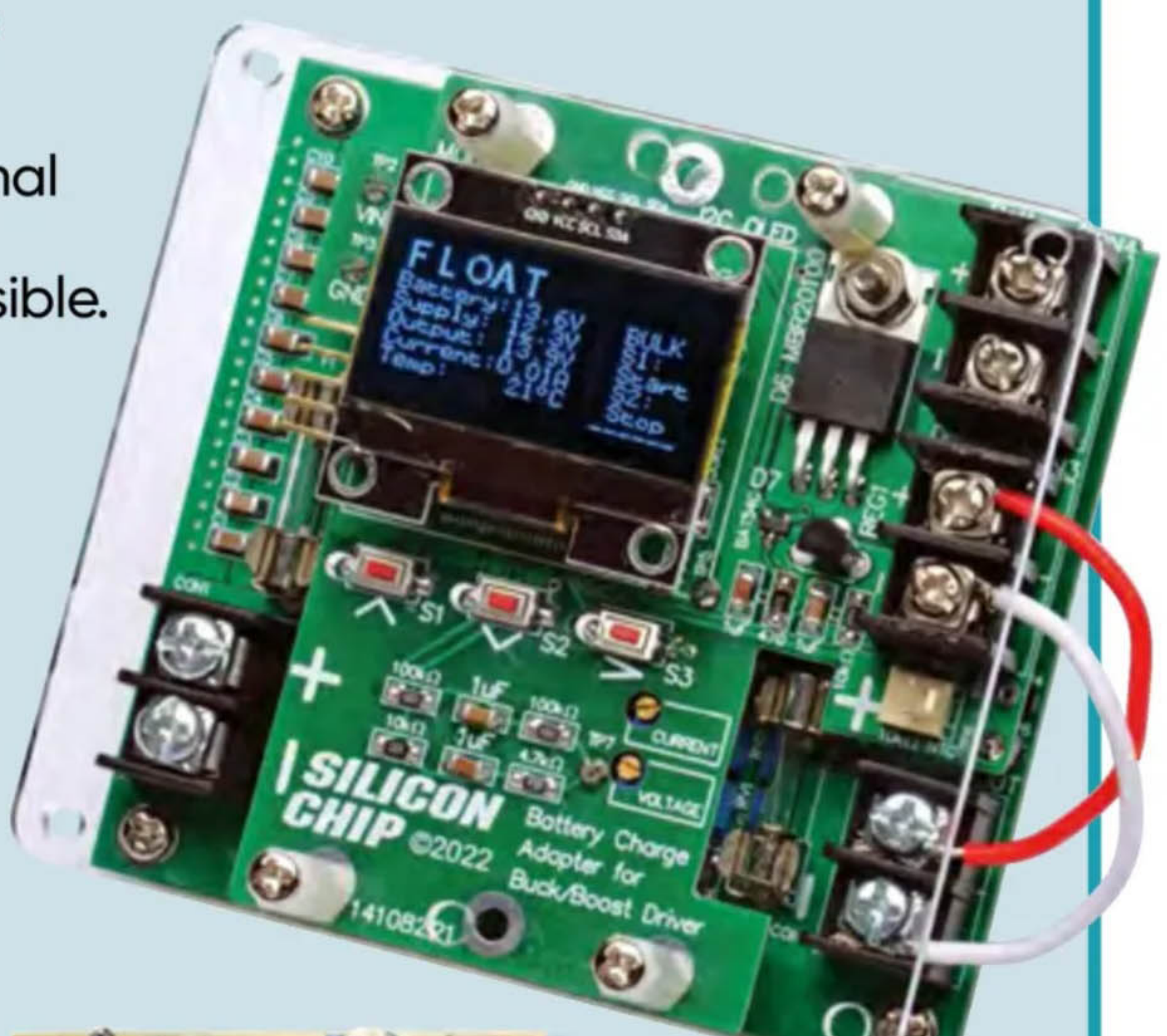
Next Month – in the October issue

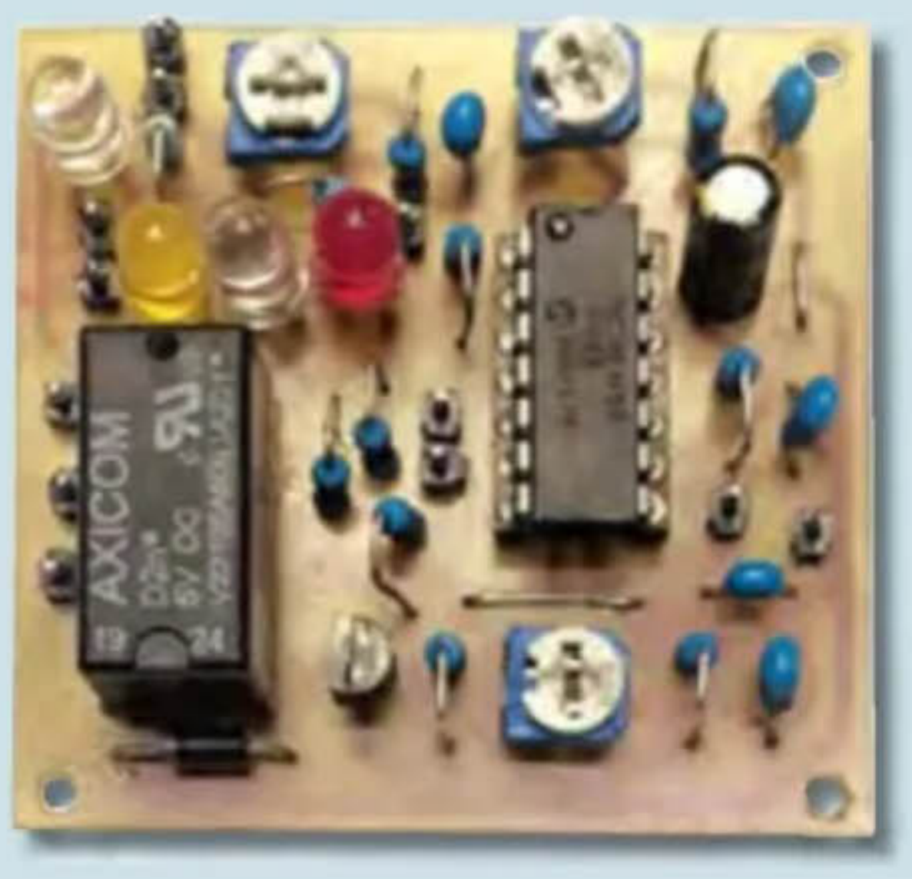


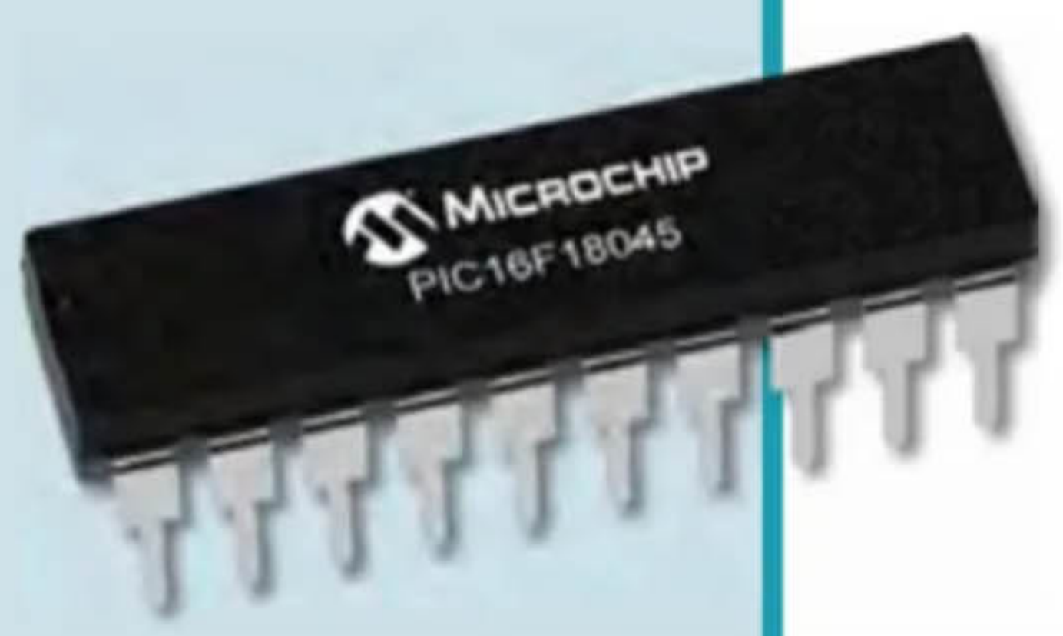
Automatic Level Crossing and Semaphore Control with chuff and whistle sounds

This project combines our Model Railway Level Crossing and Semaphore Signal projects with a Li'l Pulser Mk.2 train controller to automate a model railway layout. It also adds chuffing and whistle sounds to make it as realistic as possible.

Multi-Stage Buck-Boost Battery Charger

This simple, low-cost add-on turns our Buck-Boost Driver into a fully-featured multi-stage battery charger. It can be used with multiple battery chemistries but is especially useful for lead-acid types. Its features include adjustable absorption and float charge voltages, temperature compensation, a long-term 'storage' mode, charge status display and low quiescent current.





PIC and AVR Breakout Boards

PLUS!

New PIC & AVR Chips from Microchip

Next month, we'll have a look at some new ICs from Microchip. Plus, we have three Breakout Boards intended to plug into a breadboard while also connecting to a Snap or PICkit 4 programmer for power and programming.

PLUS!

All your favourite regular columns from *Audio Out*, *Cool Beans* and *Circuit Surgery*, to *Make it with Micromite*, *Techno Talk* and *Net Work*.

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Content may be subject to change

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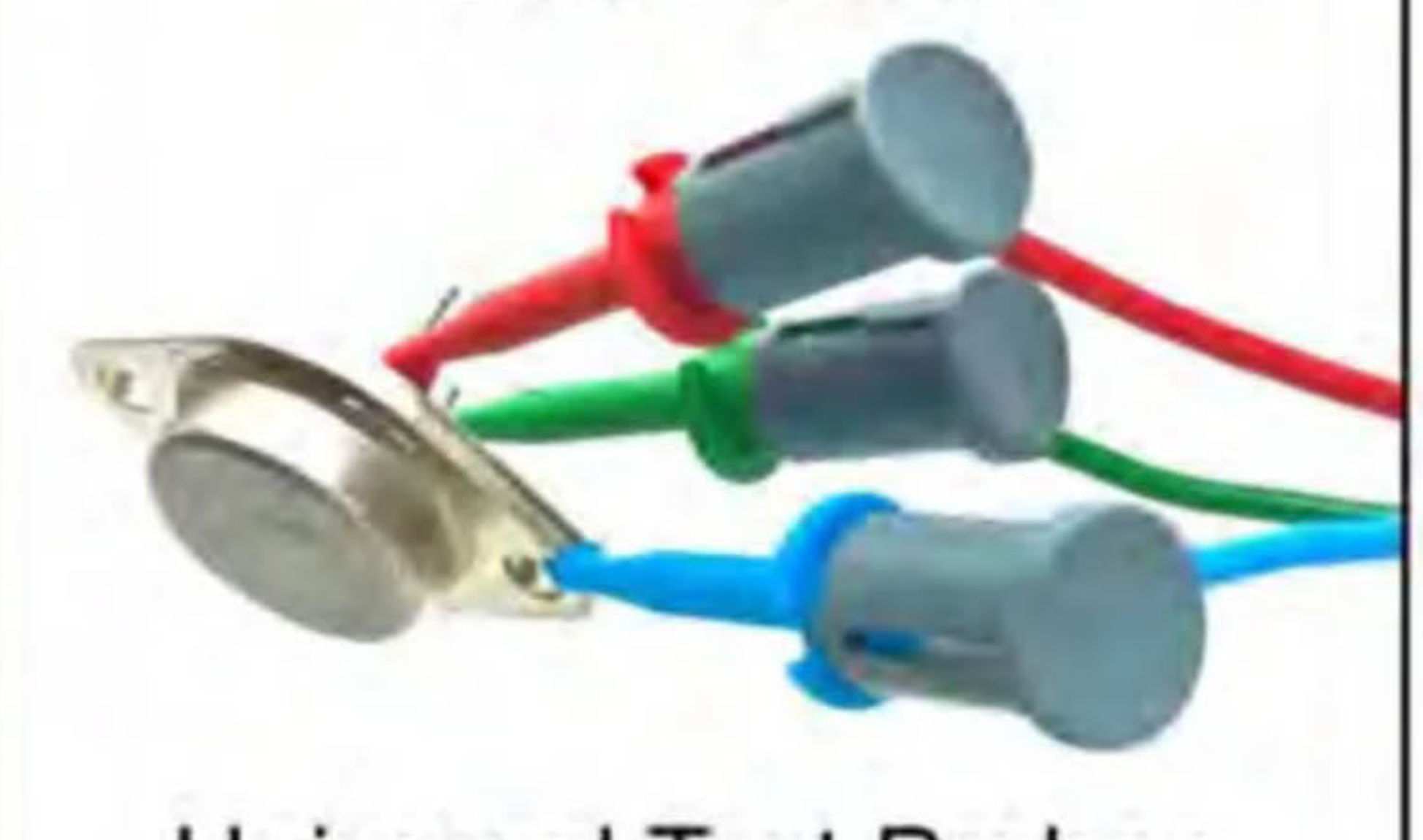

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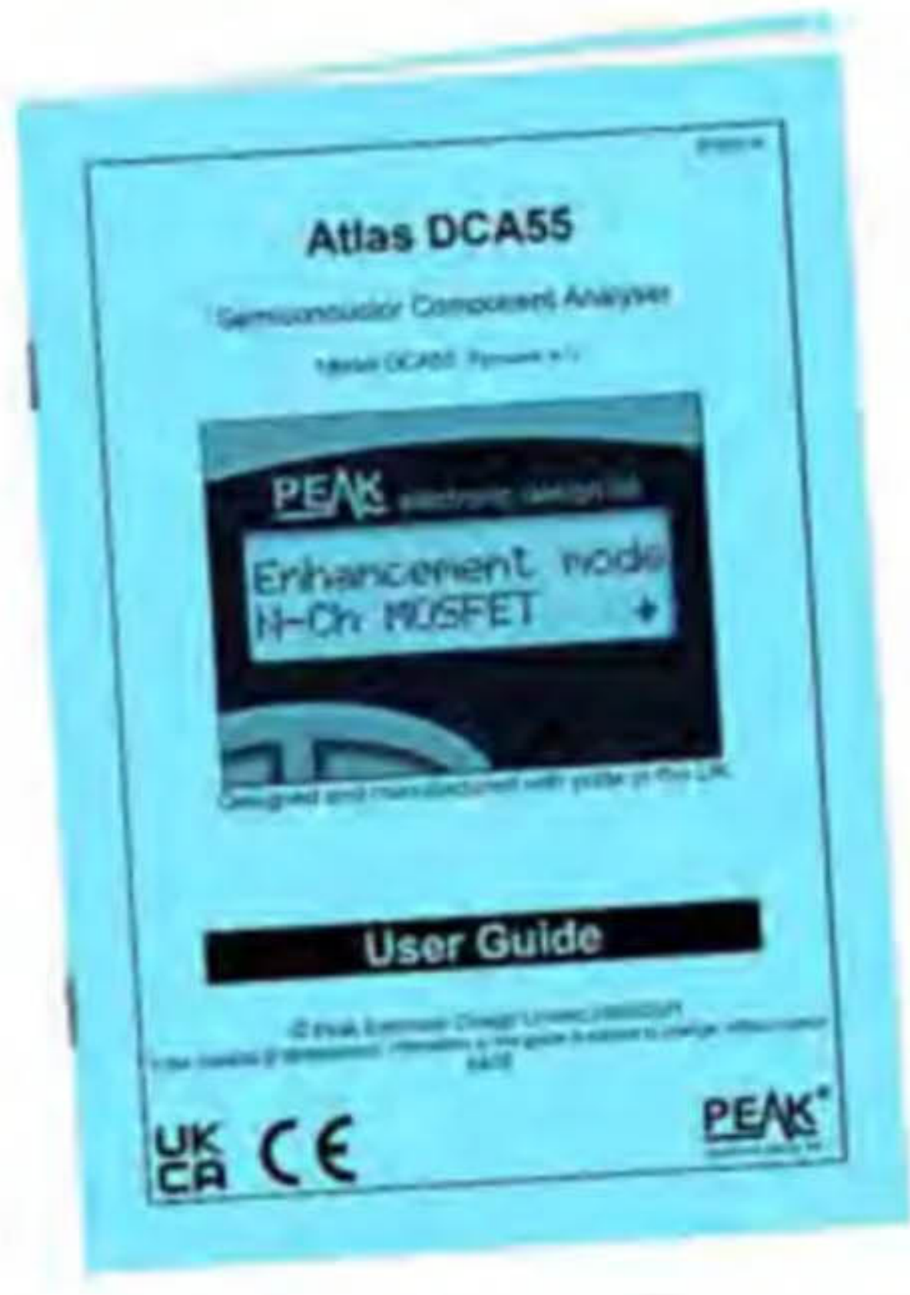
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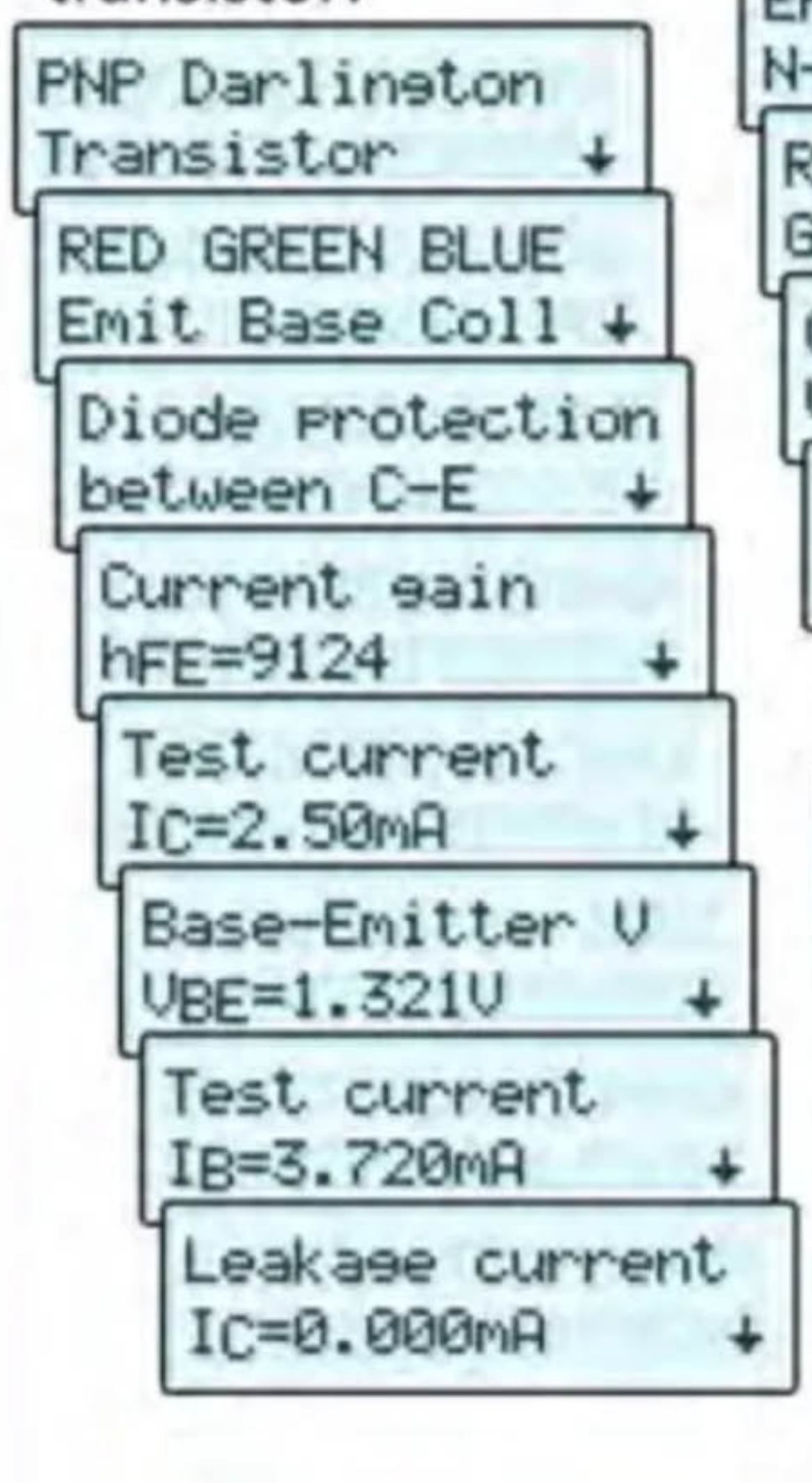
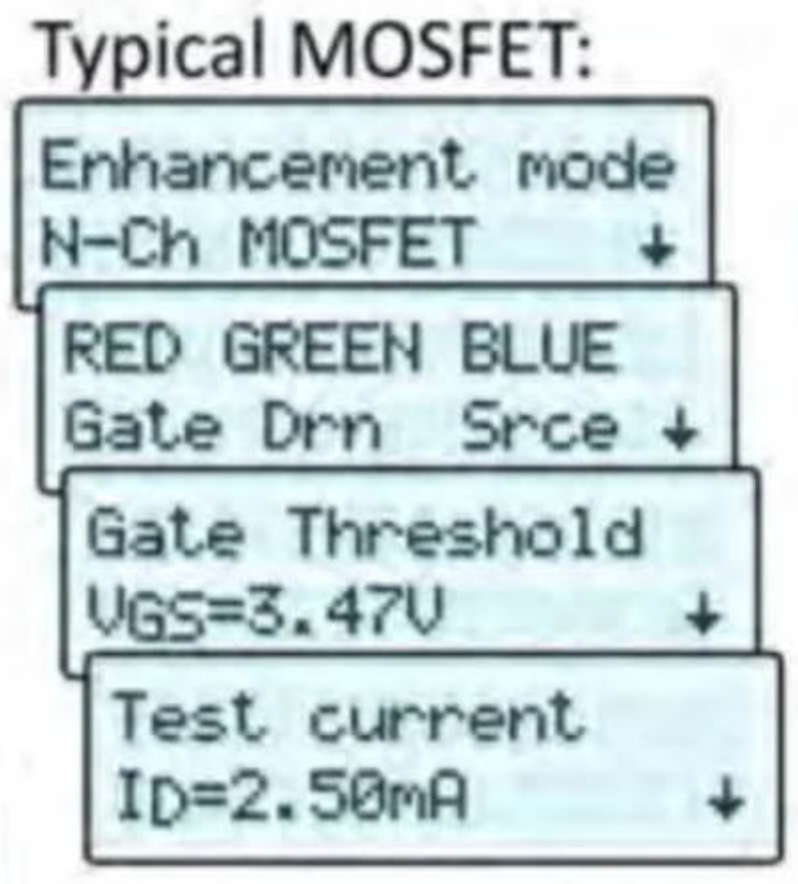
Example Screenshots

Typical darlington transistor:



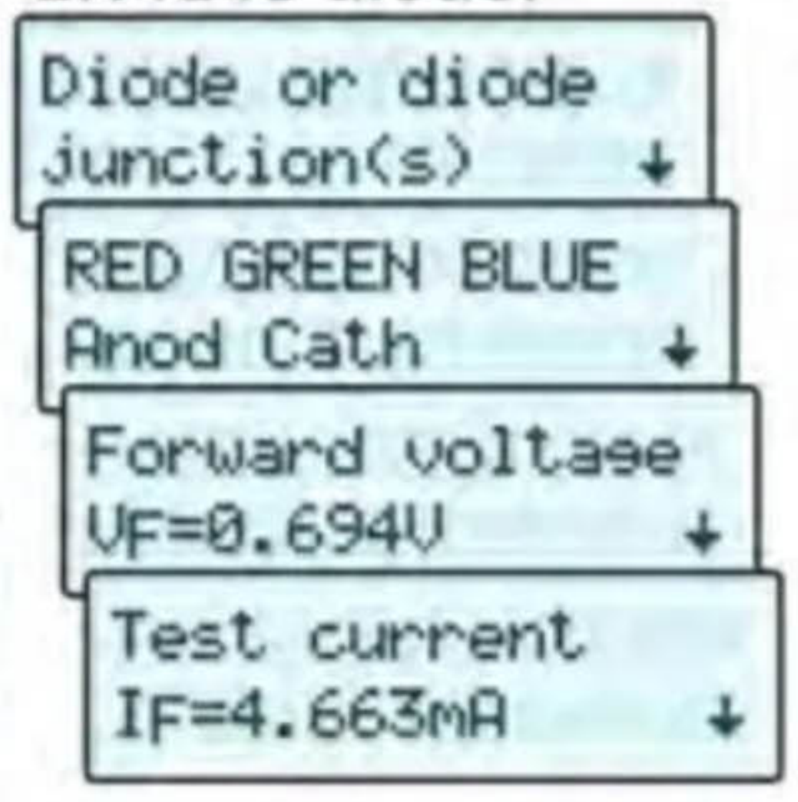
```
PNP Darlington
Transistor        ↓
RED GREEN BLUE
Emit Base Coll ↓
Diode protection
between C-E      ↓
Current gain
hFE=9124          ↓
Test current
IC=2.50mA         ↓
Base-Emitter V
VBE=1.321V        ↓
Test current
IB=3.720mA        ↓
Leakage current
IC=0.000mA        ↓
```

Typical MOSFET:



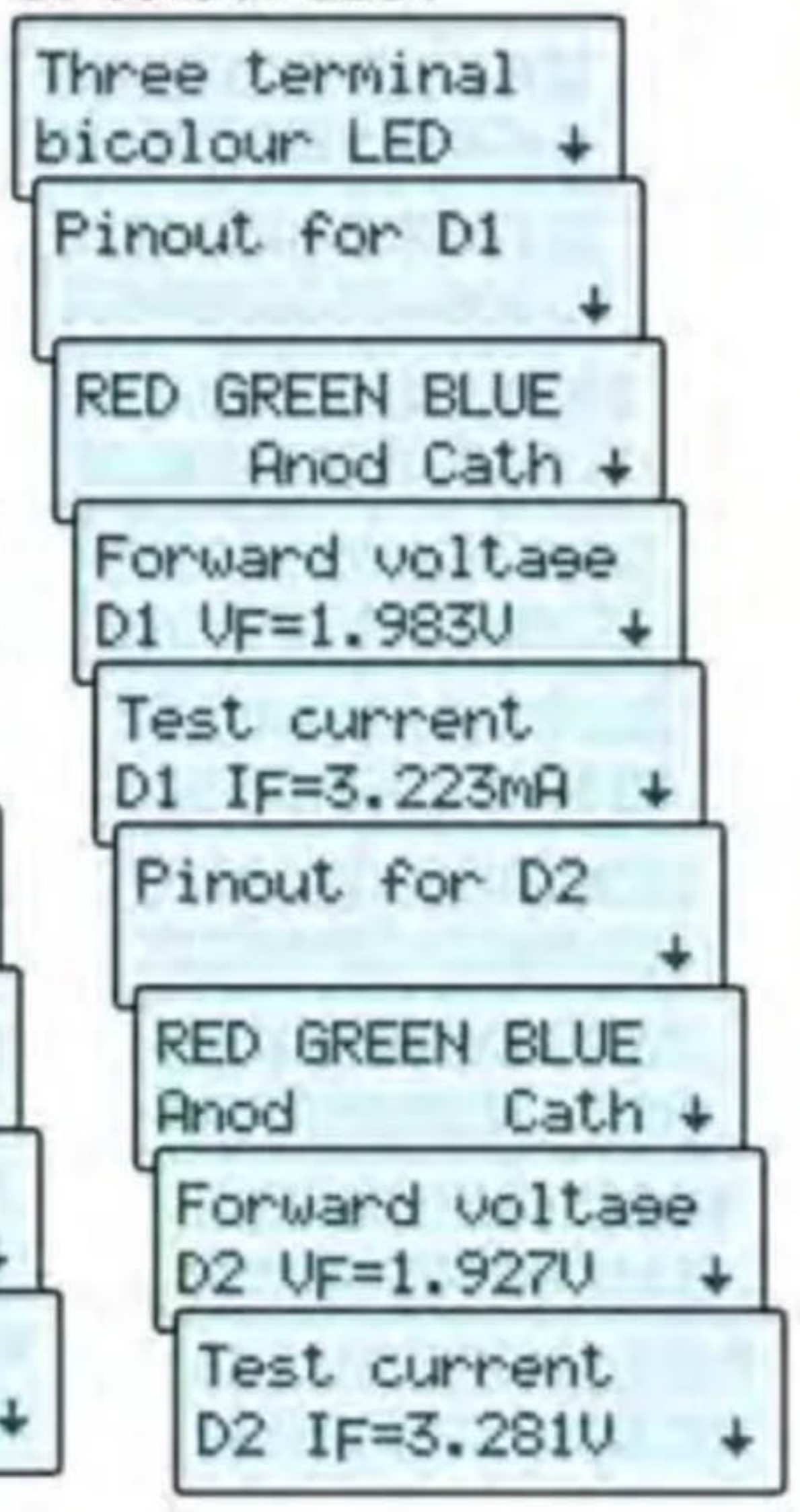
```
Enhancement mode
N-Ch MOSFET      ↓
RED GREEN BLUE
Gate Drn  Srce ↓
Gate Threshold
VGS=3.47V         ↓
Test current
ID=2.50mA         ↓
```

1N4148 diode:



```
Diode or diode
junction(s)       ↓
RED GREEN BLUE
Anod Cath        ↓
Forward voltage
VF=0.694V         ↓
Test current
IF=4.663mA        ↓
```

Bi-colour LED:



```
Three terminal
bicolour LED     ↓
Pinout for D1
                  ↓
RED GREEN BLUE
      Anod Cath ↓
Forward voltage
D1 VF=1.983V     ↓
Test current
D1 IF=3.223mA    ↓
Pinout for D2
                  ↓
RED GREEN BLUE
Anod      Cath ↓
Forward voltage
D2 VF=1.927V     ↓
Test current
D2 IF=3.281V     ↓
```

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